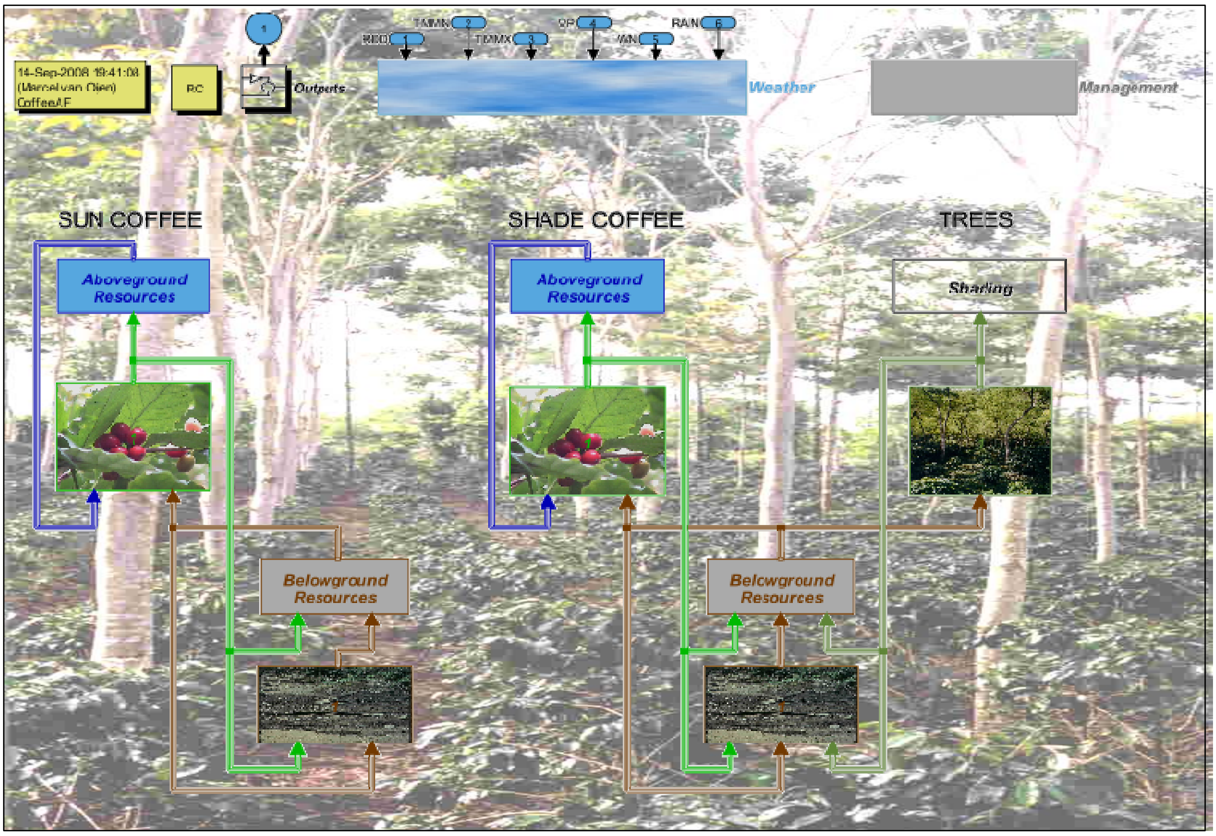
REMAL Sylvie

SupAgro 3A
Spécialisation: Production Végétale Durable

Mémoire de fin d'études :

Conceptual and numerical evaluation of a plot scale, process-based model of coffee agroforestry systems in Central America: CAF2007



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SYNOPSIS

ABBREVIATIONS

APES: Agricultural Production and Externalities Simulator

CABI: Canadian Agency for International development

CAF2007: Coffee AgroForestry 2007

CASCA: Coffee Agroforestry Systems in Central America

CATIE: Centro Agronómico Tropical de Investigación y Enseñanza

CEH: Centre of Ecology and Hydrology

CIRAD: Centre International de Recherche Agronomique pour le Développement

Hi-sAFe: Hi-silvoarable AgroForestry for Europe

INCAE: Instituto Centroamericano de Administración de Empresas

LAI: Leaf Area Index

PAR: Photosynthetically active radiation

PROMECAFE: Programa Cooperativo Regional para el Desarrollo Tecnológico de la Cafeicultura en Centroamérica, Panamá, República Dominicana and Jamaica

RRMSE: Relative Root Mean Square Error

SEAMLESS: System for Environmental and Agriculture Modeling, Linking European Science and Society

SLA: Specific Leaf Area

UMR SYSTEM: Unité Mixte de Recherche, Fonctionnement et conduite des systèmes de culture tropicaux et méditerranéens

UNA: Universidad Nacional Agraria, Nicaragua

WaNuLCAS: Water, Nutrient and Light Capture in Agroforestry System

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I- Introduction

1- Context and aim of this study

Coffee (*Coffea arabica*, L.) is a plant native from Ethiopia where it grows under highlands forests. In Central America (fig.1), it is commonly grown at altitude between 600 and 2500 m, often in association with shade trees. Its cultivation, mainly destined to exportation, contributes to income of about 265 000 producers (Muschler and Beer, 1999). The tendency of the thirty last years has been the modernization of the culture with intensified cultural practices such as fertilization, use of herbicides and pesticides and growing of more productive varieties and, in Costa Rica, reduced shading. However, the 1999's world overproduction had led to the collapse of coffee prices. Intensification of coffee production systems was no longer attractive, and the interest of producers' for shade-grown coffee increased again (Da Matta, 2004; Albertin and Nair, 2004).

Figure 1: Map of the coffee producing countries in Central America. In green are presented countries producing *coffea arabica* and in yellow, countries producing *coffea arabica* and *robusta*.

Few modeling tools are available to synthesize existing knowledge and to help predicting the effects of shade trees on coffee productivity and profitability. During the CASCA project (set up in 2001 and carried out by CIRAD, CATIE, CEH, PROMECAFE and UNA), a dynamic process-based numeric model of coffee AFS in Central America, CAF2007, was developed by Marcel Van Oijen from the Center of Ecology and Hydrology in Edinburgh. The objective of this project was to reduce vulnerability of producers face to coffee prices fluctuations. Thus, the model is expected to be used to design, in collaboration with farmers, competitive, sustainable and diversified management strategies for AFS. However, this model has not been validated and thus its potential use is still limited.

2- Interest and stake of coffee AFS in Central America

In Central America, coffee is grown under full sun or under shade depending on the type of farm (commercial vs. smallholder farms, conventional vs. organic farms…). In Costa Rica, 40% of all cultivations represent coffee monoculture and 60% represent coffee agoforestry systems with legume or timber trees (Hergoualc'h, 2008). In monoculture, coffee is generally managed intensively and production levels are higher (Da Matta, 2004). Many traditional coffee agroforestry systems include legume 'service' trees and/or valuable fast-growing timber trees as part of the shade canopy (Somarriba et al., 2001). Although production levels are lower in agroforestry systems, sustainability of the plantations is very often enhanced (Malézieux et al., 2009; van Noordwijk et al. 2003). Moreover, those types of systems provide more stable income.

However, the use of shade tree still generates debates in the coffee community (Da Matta, 2004), since almost the inception of coffee cultivation in Central America.

Several benefits of the introduction of shade trees in coffee plantation have been reported. The use of shade trees permits to attenuate extreme temperatures in both air and soil (Rebodello, 2008; Albertin and Nair, 2004; Malézieux et al., 2009), improves soil fertility through the incorporation of organic matter from leaf litter and pruning and through N-fixation capacity of some legume species (Remal and Perrin, 2009; Rebolledo, 2008). It also regulates coffee light transmission and so increase longevity of coffee plantation by reducing "die-backs" (Albertin and Nair, 2004; Robolledo, 2008) and if well managed, might meliorate system water dynamics. Introduction of shade trees also improve control of weeds, and some disease and pests (Albertin and Nair, 2004) and also improves coffee quality (Muschler, 2001). Finally, coffee agroforestry systems can contribute to biodiversity conservation (Harvey and González Vilalobos, 2007), enhance farmers' income through tree productions such as fruits, timber and services such as carbon sequestration (Nair et al. 2009) and reduction negative impacts of coffee production to environment, such as ground water contamination by fertilizers and agrochemicals (Beer et al. 1998).

Nevertheless, coffee agroforestry systems also present some disadvantages. The introduction of shade trees in coffee plantation has been shown to reduce coffee productivity above a certain shading threshold (Albertin and Nair, 2004). For example, while a high competition for resources (soil nutrients, water and light) occurs between coffee and shade tree species, coffee yield is reduced. Shade trees can also increase the incidence of some pests and diseases through increased humidity rate (Beer et al. 1998).

The final balance between benefits (positive impacts on environments) and disadvantages (productivity loss) of the introduction of shade trees species in coffee plantation is site-specific as depending on climate, soils, management practices, and shade tree species. The intensification of agrosystems have shown such limits in terms of environmental, economic and social sustainability that there is an increasing interest in valorizing eco-services that can be provided by agrosystems for the society. In this context, there is a need for better understanding of agroforestry systems' functioning to help producers adapting their systems to benefit from other opportunities. The final balance needs to be quantified for establishing the best management practices as well as for designing new coffee production systems.

3- Interests of modeling for evaluation of systems performance

Research works have permitted to identify environmental factors, management strategies and plants characteristics that affect coffee growth and yields such as the amount of radiation, the shade tree density etc. However estimations of these factors are site-specific and more often qualitative than quantitative and few studies have compared systems' performance through different climate and soil conditions (Van Oijen et al., submitted). Moreover, the coffee AFS systems present an important heterogeneity in Central America (Somarriba et al., 2001). Thus, it remains difficult to extrapolate obtained results from one site to other sites.

A way to integrate coffee AFS knowledge in order to quantify the systems' performances in different conditions is to build crop models.

Crop models are mathematical models which represent the growth and development of a crop interacting with its environment and management. In mechanistic models, dynamical biophysical processes are described through a set of equations. Those types of models are more and more developed by researchers in order to simulate the dynamical evolution of agroforestry systems where more processes are involved as results of species interactions within the association which can include shade trees in interaction with annual or perennial crops (Malézieux et al., 2008).

Crops models are often used as diagnostic tool as they can lead to a better understanding of systems' biophysical evolution and to identification of points that need to be clarified by experimentation (Boote et al. 1996). As a predictive tool, crops models permit to test effects of different factors on productivity and environmental impacts of the systems. For example, in the case of coffee agroforestry systems where management of shade trees species need to be improved to increase their sustainability (Beer et al. 1998; Somarriba et al., 2001 ; Klein et al. 2003 ; Klein et al. 2002;), analyzing quantified responses of a model to different management options can be a good way to enhance benefits and minimize negative effects of the systems. Moreover, taken into account more global issues, such as climate change, model use can be a useful tool to predict how it can impact on crops systems (Rapidel, 2008). Finally, the use of crops modeling tools also permits to reduce costs of experimentations' setting up in terms of time and money.

In order to quantify services that can be provided by coffee agroforestry systems, and taken into account potential uses of crops systems mechanistic models, which are becoming simpler to parameterize and provide more robust prediction (Van Oijen et al., submitted), such a tool can be very useful. The CASCA project had provided scientific bases for a better management of coffee agroforestry systems, a promotion of coffee quality and an improvement of producers' incomes from this crop. During this project, the first numeric model has been developed to simulate coffee agroforestry systems' productivity and environmental impacts by Marcel Van Oijen, the model CAF2007.

4- CAF2007, a process-based model of coffee agroforestry systems in Central America

CAF2007 is a process-based model developed to simulate the biophysical evolution of coffee agroforestry systems in Central America, in response to their given environment and management. Although his model has been developed with a huge bibliographic work, it has not been validated for the moment (Van Oijen et al. submitted).

For its elaboration, simple algorithms existing in crop or forestry models have been used. CAF2007 has been kept simple but can be further made more complex thanks to experimental investigation (Van Oijen et al. submitted).

CAF2007 focused on the main factors affecting coffee productivity taking into account effects of presence of shade trees. Processes described in the model and variables calculated are presented in the conceptual scheme of the model (fig.2). The detailed description of the structure of the model and a technical manual for its use are available in appendix 1 and 2. The list of parameters included in CAF2007 is available in appendix 2.

In CAF2007, weeds, diseases and pests development are not taken into account because their effects are regarded as less important, than other environmental non biotic factors, excepted for some diseases. Air pollution and soil toxicity which are difficult to simulate are also not taken into account.

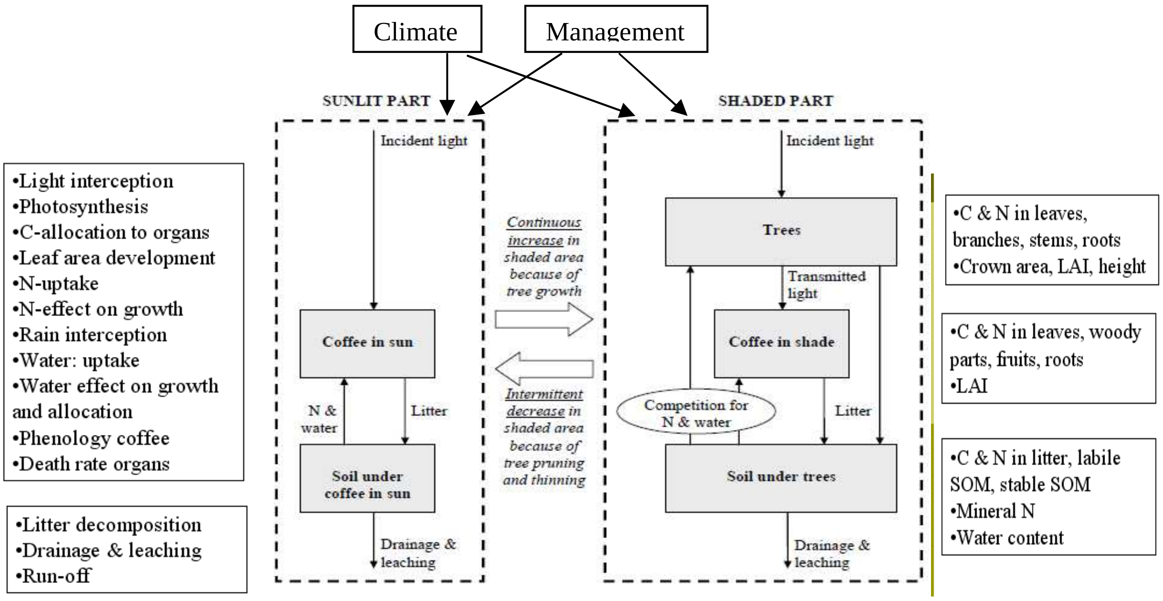

Figure 2: *Conceptual scheme of CAF2007 (Marcel Van Oijen, 2008).* The model is composed of two parts: one where coffee is grown under full sun (sunlit part) and one where it is grown under shade trees (shaded part). The two parts are interacting at a daily step. Three compartments are considered: the shade trees in the shaded part, the coffee in shade or sun and the soil under trees or under coffee in sun. The processes described are listed in the left boxes. The daily step state variables calculated for each compartment are listed in the right boxes. The upper boxes represent the climate and the shade tree, coffee and soil management. Both have an influence on both parts of the model.

5- Objectives of the study

In 2007, the Mesoamerican Scientific Partnership Platform for Agroforestry Systems with Perennials Crops has been built up between CIRAD, CATIE, INCAE, Bioversity, CABI and Promecafé. The general objective of this scientific partnership platform is to contribute to maintaining and increasing the competitiveness and sustainability of the agricultural sector of Mesoamerica through the quantification, valuing and development of the potential products and environmental services of agroforestry systems with several perennial crops, including coffee. Within this perspective, CAF2007 will be used to evaluate effects of climatic change on systems productivity and also as a helping tool to develop innovations in coffee agroforestry systems.

The objectives of the present study are (i) to do a conceptual evaluation of the CAF2007 model by identifying the main biophysical processes which need to be well simulated, and (ii) to evaluate its capacity to simulate coffee agroforestry systems' productivity by confronting simulations using data from two long-term experiments in Central America. The first part of this study, the conceptual evaluation, is based on literature review. The second part, the numerical evaluation of the model, first includes the elaboration of the database before presenting the model evaluation.

II- Material and methods

1- Conceptual evaluation of CAF2007

We first performed a conceptual evaluation of CAF2007, which means that it has been tested for its capacity to well describe the main biophysical processes involved in coffee agroforestry systems. This step was important to test if the model can be used to simulate effects of coffee agroforestry systems' management on their productivity but also on social and environmental services. By doing that, we could highlight some critical points and particularities of the model that could be further improved, focusing on coffee productivity.

CAF2007 was confronted to the existing experts' knowledge on these systems. In a previous study, Rebolledo (2008) have collected knowledge from researchers, farmers, technicians, and processors in tree Costa Rican coffee productive zones. During interviews, reproductive coffee phenological stages were identified as well as environmental factors affecting coffee yield elaboration and quality at each of those stages. This knowledge was then processed to produce conceptual models, which synthesize the information from these different sources and permit to compare them. Diagrams were obtained thanks to the AKT software and were compared to CAF2007. Based on this work and on a complementary literature review, we could identify the main biophysical processes that characterize the behavior of coffee agroforestry systems in Central America. We choose to focus on processes involving interactions between coffee and tree for light, water and nitrogen, and on the effects of those interactions on coffee productivity. We then have checked how these processes have been implemented or not in CAF2007 and if yes, in which way and in which subsystem.

Although no comparable model exist for coffee agroforestry systems, process-based models do exist, which simulate other agroforestry systems involving annual crops. The challenges that agroforestry systems pose to modelers are of similar nature across different agrosystems involving crops association. They particularly concern implementation of plants growth and development taking into account interactions between the associated species for the above and belowground resources (Malézieux et al. 2009). Therefore, we continued the conceptual evaluation by comparing the biophysical processes' implementation and focus of three other existing agroforestry models:

- **APES** model, which simulates temperate annual crops systems but also vineyard in association with grass. This model was developed within the European project SEAMLESS for integrating analysis of impacts on systems' sustainability and multi-functionality (Donatelli et al., submitted, Aurélie Metay et Eric Casellas, personal communication).
- **Hi-sAFe** model, which simulates temperate systems involving annual crops and trees. This model has been developed within the European project SAFE to predict evolution of intercrops' productivity and trees' growth and estimate the environmental budget of the systems in terms of carbon, nitrogen and water (Dupraz et al., 2004; Lecomte I. 2006, Grégoire Talbot, personnal communication).
- **WaNuLCAS** model, which simulates a lot of different types of systems involving perennials or annuals crops and trees. This model has been performed to evaluate systems' sustainability and profitability, focusing on belowground interactions (Van Noordwijk and Lusiana, 1999).

Among the biophysical processes, we chose to focus the comparison on the models' implementation of:

- Plants' phenological development, taking into account interactions between species.
- Plants' growth and calculation light interception, carbon assimilation and allocation to harvested organs, including plants' reserves dynamics, particularly for perennials crops as they are more likely to develop a strategy of reserves accumulation during their cycle.
- Inter-specific competition for below-ground resources, in particular water and nitrogen, with a regard on relative environmental impacts, in particular N-leaching, run-off and soil erosion.

2- Numerical evaluation of CAF2007

A literature review done by Marcel Van Oijen (Van Oijen, submitted) gives an overview of available quantitative data on coffee agroforestry systems for diverse combinations and localizations in Central America. A first model parameters' calibration has been done from this review although information on climate, shade trees and coffee plants were limited.

In our study, we chose to work with data sets from two long-term trials established in 2000 by CATIE in two different agroecological zones, in Costa Rica and Nicaragua, in order to compare coffee agroecosystem performance under full sun, legume and non-legume shade types, and intensive and moderate, conventional and organic inputs.

A- Experimental design

The first trial is situated in a low (685 meters above sea level) humid tropical zone (3200 mm annual rainfall), in CATIE in Turrialba in Costa Rica and the other one in a low (455 meters above sea level) but more arid zone in Masatepe in Nicaragua (1470 mm annual rainfall) with a marked 6-month dry season (less than 50 mm per month). In both trials, main treatment plots are different shade tree combinations with subplots for input levels for nutrient and pest management. However shade trees species, which are the most common species used in association with coffee, differ between both sites (tab 1). Each trial has a full-sun treatment and different combinations of shade tree species to represent a gradient of nitrogen fixation and contrasting combinations of evergreen/deciduous and canopy type. Four inputs treatments have been implemented: two levels of organic management and two level of conventional management (tab.2).

Table 1: Tree species used in shade combinations in:

a) Turrialba, Costa Rica

Species	phenology	canopy shape	N-fixing	use
Terminalia amazonia (TA)	evergreen	high compact	No	timber
Chloroleucon eurycyclum (CE)	evergreen	high spreading	Yes	timber
Erythrina poepiggiana (EP)	evergreen	low compact	Yes	service

b) Masatepe, Nicaragua

Species	Phenology	canopy shape	N-fixing	use
Simarouba glauca (SG)	Evergreen	high narrow	No	timber
Tabebuia rosea (TR)	Deciduous	high narrow	No	timber
Samanea saman (SS)	Evergreen	high spreading	Yes	timber
Inga laurina (IL)	Evergreen	low spreading	Yes	service

Table 2: Input levels for nutrient and pest management in coffee systems experiments

Input type	**Organic**	**Organic**	**Chemical**	**Chemical**
Name of treatment	**Moderate Organic**	**Intensive Organic**	**Moderate Conventional**	**Intensive Conventional**
Type of soil amendments	Coffee wastes	Coffee wastes, chicken manure, ground rock minerals	Chemical fertilizer at half rate	Chemical fertilizer at recommended rates for full sun coffee
Disease management	None	Use of botanical and mineral foliar applications	Use of infrequent commercial fungicide applications	Regular use of commercial fungicides
Insect pest management	Gleaning of berries after harvest	Manual practices and use of botanical and biological applications	Manual practices and infrequent use of commercial insecticides	Regular use of commercial insecticides
Weed management	2-4 routine machete weedings per year	Manual selective weed management between row and clean within row area	Selective weed management between row and clean within row area with manual and herbicide	Maintain bare soil with herbicides

Organic and conventional fertilizer rates changed over time depending on the whether during coffee growth phase (first 2 years) or productive phase, and subsequently adjusted based on the results of soils analysis and changes in soil fertility. Those rates were around 150 kgN/ha/y for the moderate conventional inputs level, around 300 kgN/ha/y for the intensive conventional one, around 9 t/ha of coffee pulp for modertae organic one adding 7 t/ha of chicken manure for intensive organic one (J. Haggar and E. de Melo, personnal communication). Figure 3 represents the annual technical itinerary developed in both trails.

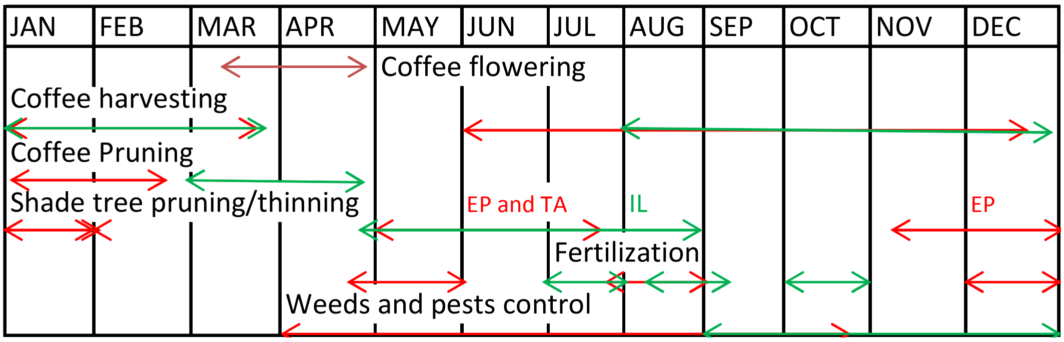

Figure 3: Technical itinerary in coffee agroforestry trials in Turrialba (red) and in Masatepe (green). Coffee flowering period is also indicated.

Main plots and subplots treatments combinations are presented in Table 3. Three replicas were established at each site forming a randomized block design with shade as main treatments and inputs as subtreatments within shade. Subplot size varied between 500-600 m^2, with measurement plots of 225-300m^2 (minimum of 24 shade trees and 100 coffee plants). The full experiment covers 6 ha in Costa Rica and 3 ha in Nicaragua.

Table 3: Main plot and subplot treatments combinations in

a) Costa Rica

Main plot	Full sun FS	*Erythrina* EP	*Terminalia* TA	*Chloroleucon* CE	*Terminalia* *Chloroleucon* CETA	*Terminalia* *Erythrina* *EPTA*	*Chloroleucon* *Erythrina* CEEP
Subplot	IC, MC	IC, MC, IO, MO	IC, MC, IO, MO	MC, IO	MC, IO	MC, IO	IC, MC, IO, MO

b) Nicaragua

Main plot treatments	Full sun FS	*Simarouba,* *Tabebuia* SGTR	*Tabebuia,* *Samanea* SSTR	*Simarouba,* *Inga* ILSG	*Inga* *Samanea* SSIL
Subplot treatments	IC, MC	IC, MC, IO, MO	MC, IO	MC, IO	IC, MC, IO, MO

Coffee was planted at 4000 plants per hectare in Nicaragua and 8000 plants per hectare in Costa Rica, the latter was achieved by planting two plants per planting hole – a common practice in Costa Rica. Coffee bushes were selectively prunned after each harvest in order to decrease the amount of old branches and stimulate the production of new productive tissues. Shade trees were planted at 667 trees per ha in Nicaragua and 417 trees per ha in Costa Rica, 4 times their expected final density, and have been reduced by 50% by two thinnings. In Nicaragua the legume timber tree originally selected and planted was *Enterolobium cyclocarpum*, however, after two years tree growth was very low and variable, thus it was considered necessary to replace it with *Samanea saman*, which was planted in 2002.

In Costa Rica *Erythrina* shade trees are generally pruned two times each year leaving only the main trunk to a heigth of about 1.5 – 2.0 meters. However, based on recent studies in Costa Rica (Muschler, 2001) of the effect of shade levels on coffee quality, *Erythrina* management was varied by treatment. In the IC treatment, *Erythrina* is pruned completely twice a year, one time after coffee flowering and one after harvesting. However, in all the other treatments with *Erythrina*, a minimum of three branches were left for partial shade cover after each of the two annual prunings. Temporary shade was not initially included in the establishment strategy in Costa Rica. However, temporary shade of *Ricinus* was incorporated after coffee planting to suppress weed growth and to improve coffee plant survival during transplanting.

In Nicaragua the initial establishment plan included the use of temporary shade for all treatments with permanent shade. *Ricinus comunis* was the non-N fixing species, while *Cajanus cajan* was the N-fixing species. Temporary shade was planted between every coffee plant and then thinned to provide biomass for soil improvement and to achieve shade to suppress weeds and diminish light intensity for young recently planted coffee plants. Timber species are pruned to achieve a marketable main trunk, removing lower branches, while *Inga* is pruned once per year for more uniform shade distribution.

Both sites, localized in different climatic zones, present also different coffee, shade trees and soil management. These contrasts represent an interest in the present study which final objective is to test the performance of the model to be used as a diagnotic and predictive tool for coffee agoforestry systems in different environmental and management conditions.

B - Choice of the plots

As the model CAF2007 takes only N-mineral fertilization into account, we first chose to work with data from subplots managed with conventional fertilizers: Intensive Conventional and Medio Conventional. Moreover, the model can include only one shade tree species in association with coffee, so that we have eliminated combinations involving more than one species in Turrialba. In Masatepe, all the combinations involve two shade tree species. However we chose to work with data from subplots including Samanea saman, as it was planted in 2002 and until the year 2006, as trees were too well developed after to consider only one species. We also ignored the presence of temporary shade at trials establishments as we couldn't implement it in the model. This could lead to problems while evaluating the model; simulated yields might be lower because it will not take into account the fact that this presence improves the establishment of the coffee plant and soil fertility.

In Turrialba we have collected data from subplots with both levels of conventional managements (IC and AC) for full-sun plots and combinations with the N-fixing species *Erythrina poepiggiana* also present in CAF2007 and with the timber tree species *Terminalia amazonia*, as this species is of the same gender than *Terminalia ivorensis*, already present in the model. In Nicaragua, we also collected data from subplots with conventional management levels for the full-sun plots and for the combination with the N-fixing tree species *Inga laurina* in association with *Samanea saman* which has been ignored. This species was compared to *Inga densiflora*, the only species of same gender included in the model.

We finally worked on 5 treatments for two level of inputs; 6 subplots in Turrialba and 4 in Masatepe. This leads to the possibility to test the model in 10 different situations in terms of climate but also coffee, tree and soil management.

C - Data collect

Climatic data

The first step to compare model outputs with observed data from the chosen subplots was to collect climatic data since trials establishment in 2000. CAF2007 requires six daily weather data (appendix1); daily maximum and minimum temperature (°C), wind speed (m/s), photosynthetic active rate (MJ/m-^{2}), vapor pressure (kPa) and rain (mm).

Model initialization

We then selected the data needed to initialize the model with a maximum of subplot-specific initial state variables. As presented in table 4, the model requires 4 state variable for shade tree, 4 for coffee and 7 for soil.

Management

The model also requires 3 parameters for coffee management; the first day of pruning, the interval between two pruning and the fraction of pruned biomass, 6 parameters for shade tree management; the first day of pruning, the interval between two pruning, the fraction of pruned biomass, the two dates of thinning, the fraction of thinned biomass, and the initial tree density, and 4 parameters for soil fertility management; the three dates of fertilizer application, and the application rates.

Coffee yields

We also needed to have annual coffee yields in both sites in order to compare them with simulations. The model calculates annual yields in tons of coffee beans cry matter per hectare while they are measured in Costa Rica in the local volume unit cajuelas of green coffee at a humidity rate of 12% per subplot per year and in Nicaragua in kilograms of coffee berries at a humidity rate of 12% per subplot per year. Thus, data needed to be converted in order to allow a comparison.

Other data

Finally, we searched for more data in all the other studies made by researchers and students on the subplots in order to have a maximum of data to compare with the model outputs, such as the carbon biomass after a pruning, the tree height, the shade area, the quantity of carbon into the soil.

Table 4: Initial state variables required by CAF2007 and their default value

	Parameter	**Identifier**	**Unit**	**Default data**
Tree	Initial C biomass in branches	CB0T	kg C m^{-2}	0,10
	Initial C biomass in leaves	CL0T	kg C m^{-2}	0,05
	Initial C biomass in roots	CR0T	kg C m^{-2}	0,20
	Initial C biomass in stems	CS0T	kg C m^{-2}	0,10
Coffee	Initial biomass leaves	CL0	kg C m^{-2}	0,05
	Initial biomass storage organs	CP0	kg C m^{-2}	0,00
	Initial biomass roots	CR0	kg C m^{-2}	0,05
	Initial biomass stems plus branches	CW0	kg C m^{-2}	0,05
Soil	Initial amount of litter	CLITT0	kg C m^{-2}	0.33
	Initial concentration of C in organic matter	CSOM0	kg C m-2	11,00
	Initial fraction of the soil organic matter which is unstable	FCSOMF0	-	0,64
	Initial C/N ratio in litter	CNLITT0	kg C kg-1 N	17,00
	Initial C/N ratio in unstable organic matter	CNSOMF0	kg C kg-1 N	12,00
	Initial values NMIN	NMIN0	kg N m^{-2}	0,001
	Initial C/N ratio in stable organic matter	CNSOMS0	kg C kg-1 N	11,00

Measurement of Specific Leaf Area

A parameter has been directly measured in the trials during the study, the Specific Leaf Area of each shade tree species and the maximum and minimum Specific Leaf Area of coffee. In the model, growth organs rates are calculated in term of carbon biomass. This parameter permits to calculate daily coffee and shade tree leaf area index from the leaf biomass. Those latter variables contribute to determine the carbon coffee production and also the effect of tree shading on coffee. So it was interesting to obtain the values of theses parameters for each treatment where we choose to calibrate and test the model.

To measure specific leaf area of shade tree species, for each treatment, we collected five leaves per branch and one branch per tree for 5 shade trees. To measure maximum and minimum specific leaf area of coffee, young, mature and old leaves were collected separately. For each treatment and each leaves category we selected ten plants and took five leaves per plant. This measurement has been done for both sites.

Leaf areas were measured and leaves were dried at 60°C during two days and then weighted. The specific leaf area of each tree species present in the chosen treatment and both maximum and minimum specific leaf area of coffee were determined.

Literature review

As we have already noticed before, a previous literature review has been done by Marcel Van Oijen during the model construction. For some parameters, data were found available in some studies. Although those data are sometimes very contrasting, they constitute a good reference for the model elaboration (Marcel Van Oijen, personal communication).

D - Sensitivity analysis of CAF2007

Local sensitivity analysis was performed in order to have an idea of the sensitivity of the model outputs to the variation of parameters values. Sensitivity analysis permits to investigate how the variation in the outputs of a model can be attributed to variation in the inputs. Thus, this method can be used to do a diagnostic of a model to understand how the model's outputs respond to changes in the inputs which are the initial state variables and parameters. By doing this analysis, we could determine factors that mostly contribute to the outputs' variability (Satelli et al., 2000; Monod et al., 2006).

We varied the value parameter by parameter and checked the obtained seven chosen outputs of the model listed in Table 5. These outputs were chosen according to the objective of the model to be used to assess agroforestry systems productivity and environmental impacts for different management and climatic conditions. We defined a minimum and a maximum value for each parameter according to literature review done by Marcel van Oijen and discussion with experts.

Table 5: The 7 outputs, out of the 32 existing, chosen for the sensitivity analysis

Output	**Unit**
Average coffee productivity	ton DM ha-1
Average wood productivity	m3 ha-1 y-1
Average N-emission	kg N ha-1 y-1
Average N-leaching	kg N ha-1 y-1
Average C-sequestration on-site	t C ha-1 y-1
Average C-soil run-off	t C ha-1 y-1
Average water drainage	mm d-1

We then wrote scripts (see appendix 2) to generate outputs for each value with a fixed interval for each parameter. The 7 outputs values obtained for each value of each parameter were saved and coefficients of variation have been calculated for each one and each parameter. The coefficient of variation is unitless and thus can be compared relatively. Results were interpreted to have an idea of the most sensitive outputs and the most influent factors in the model.

E- Evaluation of CAF2007

Evaluation was performed for both moderate and intensive conventional inputs levels in order to test the capacity of the model to simulate effects of nitrogen limiting-factor on systems' productivity. Model's outputs were generated with default data inputs and with collected data to test the model's need for site-specific inputs data for being more performing.

To compare CAF2007 with data, we edited graphs of model annual coffee yield predictions versus observed value, of differences between measured and calculated values against measured values because they are easier to evaluate and compare. To measure agreement between measured and calculated values, we also calculated the relative root mean square error, or 'general standard deviation', whose advantage is to be unitless and thus easier to compare (Mayer and Butler, 1993). All those methods are very often used for crops models' evaluation (Mérot et al., 2008; Wallach, 2006).

The relative root mean square error (RRMSE) is given by:

$$RRMSE = \sqrt{((\sum (Yi-yi)^2)/N)}/\square$$

Where:

- Yi is the observed annual coffee yields for the year i
- yi the simulated annual coffee yields for the year i
- N is the number of year of simulation
- □ is the average of Yi values

More the value of RRMSE is high; more model simulations are different from observations, which mean that model doesn’t predict well the annual coffee yield of the system. On the contrary, more this value is low, more model simulations are closed to observations and the model is considered more reliable. This value has been used to compare the performance of the model to simulate the coffee productivity among the different subplots.

III- Results and discussion

1- Conceptual evaluation of CAF2007

As a result of the conceptual evaluation, four biophysical processes were identified important to be correctly simulated by the model; (i) the effect of shading on reproductive dynamics, (ii) the coffee carbon production and organs allocation, (iii) nitrogen dynamics and (iv) water dynamics. These processes were chosen because they involve interactions between species for light, water and nitrogen and contribute to explain the observed variations in coffee yields and thus need to be well implemented in CAF2007.

a- Effect of tree shading on coffee reproductive dynamics

The first critical we pointed deals with coffee phenology and particularly its reproductive stages because it has been shown that effects of environmental factors on the reproductive stages contribute to determine the final coffee yields (Rebolledo, 2008). Moreover, the reproductive cycle of coffee plant takes place 8 to 10 months per year (Frank, 2005). In her study, M. Rebolledo listed 5 coffee phenological stages (fig.4) and reported the effects of environmental factors on each of those stages by processing conceptual models.

It has been observed that sufficient period and intensity of radiation, temperature or water stress followed by a sufficient amount of rain contribute to determine coffee flowering activation and intensity (Rebolledo, 2008; Franck, 2005; Drinnan and Menzel, 1994). This process is very specific to coffee. Intensity of flowering (amount of fertile flowers), and so potential productivity of coffee plants, is also governed by the amount of vegetative nodes produced the preceding year. During fruits growth, vegetative growth can also takes place leading to higher competition for carbon between fruits and leaves. This phenomenon is at the origin of the “tired” status of the coffee plant. Radiation, temperatures, wind and amounts of rain can also have effects on fruits growth and maturation. (Rebolledo, 2008; Kanten and Vaast, 2006; Drinnan and Menzel, 1995).

Tree shading has an influence on environmental factors controlling coffee reproductive dynamics by modifying microclimate. A study made in different coffee agroforestry systems in Perez Zeledon, Costa Rica reported different impacts of shade trees on coffee vegetative and reproductive growth according to the species (*Terminalia ivoriensis, Eucalyptus degupta* and *Erythrina poepigiana*) (Angrand et al., 2004). The vegetative growth was enhanced in all agroforestry systems compared with full sun system and the higher increase was obtained under *Terminalia ivoriensis*. However, flowers number per productive node was higher in full sun compared to the three agroforestry systems because of their buffering effect on coffee water and temperature stress which determine flowering intensity. However, the number of fruit number per productive node was higher in agroforesty systems than in full sun because of the higher fruit falling rate in full sun system.

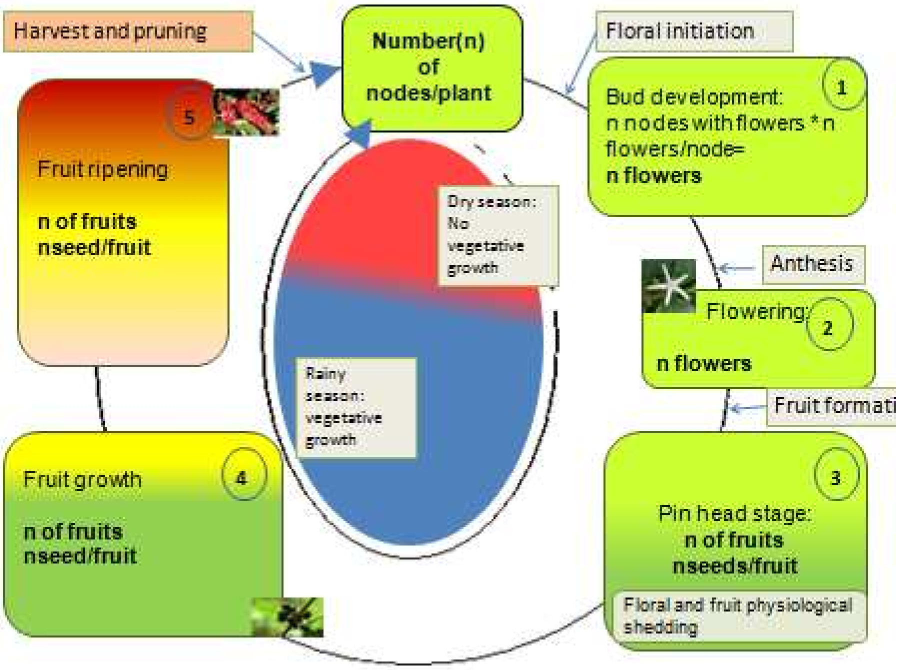

Figure 4: The five coffee phenological stages (Rebolledo, 2008)

Another study, made in 1997 by Estivariz Coca in the region of Turrialba, Costa Rica compared coffee flowering and production under homogeneous and heterogeneous shade of *Erythrina poeppigiana* and at different distances from shade trees. In this study, the light was the only production-limiting factor. The homogeneous shade was provided by tall trees which selectively pruned allowed 40 to 60% of the photosynthetically active radiation (PAR). The heterogeneous shade was provided by trees drastically pruned to allow more than 80% of the PAR. There were no significant differences among the number of flowers and fruits between both shades. In fact, the flowering peaks were more related to precipitation and temperature patterns of the studied site. However, the conversion rate from flower to fruit was lower under homogeneous shade. Homogeneous shade also slew down the vegetative growth and so the potential coffee production compared to heterogeneous shade. Moreover, the morphological variables of shade trees (crown diameter, height and productive basal area) were correlated to coffee production. Distance to the nearest tree did not show a significant effect on flowering and on potential production. These results indicate that the effects of shade trees on coffee reproductive dynamics can vary according to the shade trees species and the intensity of shading.

In CAF2007, the different 5 phenological stages listed in the conceptual model (Rebolledo, 2008) have not been implemented. Although the coffee phenology module is more empirical, it stays specific to coffee production systems. Two key phenological events are taken into account:

- the flowering starting day which is simulated as the first day of the year with a fixed minimum amount of rain. This implementation seems to be concordant with observations in coffee plantations in Central America (Rebolledo, 2008; Franck et al., 2006; Estivariz Coca, 1997)

- the day of fruits maturation which is also the harvesting day. It is determined by a fixed sum of temperature (Franck et al., 2006), without taken into account effects of amounts of radiation and rains, and forced to happen before the end of the year if the fixed temperature sum is not reached. This is also relevant with observations because farmers try also to avoid this overlap by pruning trees to accelerate fruits maturation (Rebolledo, 2008).

This implementation differs from the three numeric models where annuals and perennials crops' phenological stages involved in both vegetative and reproductive growth are determined by temperature sum and are taken into account for calculation of crops growth rates (appendix 1).

The intensity of coffee flowering, which represents the potential production, is taken into account in the model while calculating the fruit sink strength directly at the flowering starting day. This sink strength is then used to calculate fraction of carbon allocated to coffee beans. The fruit sink strength increases with the average of photosynthetically active radiation of the previous thirty days. This is in concordance with the conceptual model where flowering intensity is increased by an irradiative stress. However, water and temperature stress also previously reported are not taken into account in the model to calculate this strength.

This implementation is original compared to the other numeric models. In the model Hi-safe for example, grains yield is calculated with a harvesting rate that increases linearly with the temperature sum during the grains filling stage. In the model APES, the biomass is distributed in the storage organs according to allocations tables at each phenological stage. In CAF2007, calculation of flowering intensity is function of radiation experienced by coffee around flowering. Nevertheless, by calculating the sink strength directly, all the other environmental factors, such as wind and temperature, influencing amounts of fertile flowers and fruits reported in the conceptual model are ignored. Moreover, the fact that only one day of flowering and harvesting is simulated seems not realistic as it doesn't consider the coffee flowering waves. In fact, crazy flowering happens when flowers open on different times and leads to delayed time of fruits maturation.

b- *Coffee carbon production and allocation*

An interest was also given to the implementation of coffee carbon production and particularly its allocation in the model.

Photosynthesis depends on factors such as radiation, temperature, CO2 atmospheric concentration, water and nutrients availability, fruits load, leaf age, and plant genotype. Moreover, it has been shown that stomata limitations reduce photosynthetic activity. Carbon assimilation can be affected by microclimate, when the effect of fruits as a sink is eliminated. As a result from the modification of carbon assimilation, a seasonal pattern has been proposed: roots development during the dry season and aerial development during the rainy season (Rebolledo, 2008).

In the conceptual model (fig. 5), high amount of radiation increases the flowering intensity so that the fruits demand for carbon can become higher than the leaves demand. Thus, it is sometimes difficult for coffee plants to response to the high demand level for carbon and allocation very often favors to fruits, causing "die-back" of coffee plants. The bi-annual effect observed on coffee yields can be explained by this carbon competition. A good production one year is often fallowed by a poor one because an important fraction of the carbon has been allocated to the fruits and thus the vegetative organs are not enough strong to permit high production levels the following year. This effect is limited in agroforestry systems because of the lower fruit sink strength compared to source strengths. Thus, shade can improve longevity and stability of coffee plantations.

Furthermore, in 2006, Frank et al. have shown that there is a source–sink down-regulation of carbon assimilation rate. In fact, when fruit demand is high, carbon assimilation rate is increased. This is explained because assimilated sugars are exported from leaves to fruits. When this demand is low, sugars are accumulated in leaves reducing carbon assimilation rate by feed-back. Thus, this mechanism can limit coffee photosynthesis, especially when plants are grown in agroforestry systems and carry low fruit loads. Coffee carbon assimilation rate decreasing with light intensity have also been explained in other studies as an adaptative strategy of coffee as a shade plant (Da Matta, 2005; Van Oijen, 2004). Coffee plants can also constitute reserves of carbon as starch which can be mobilized when fruits demand is higher than photosynthetic capacity (Rebolledo, 2008).

According to these studies, it seems important to check if the bi-annual dynamics, reserves dynamics and effects of fruit sink strength on carbon assimilation rate are taken into account in CAF2007 in yields calculation.

In CAF2007, light interception is modeled by Beer’s law with a constant light extinction coefficient as fallowing:

$$\text{PAR intercepted} = \text{PAR} * (1 - \exp(-\text{KEXT} * \text{LAI}))$$

Where:

- PAR is the photosynthetically active radiation
- KEXT is a fixed coffee light extinction coefficient
- LAI is the coffee leaf area index

Assimilate production of carbon is then calculated by multiplying the PAR intercepted by coffee with the light-use efficiency (LUE). LUE is computed from atmospheric CO2 concentration, temperature, light intensity, upper leaves RUBISCO content, and coffee light extinction coefficient and photoperiod duration. LUE decreases with light intensity which is consistent with high rates of photosynthesis observed at low light intensity. Carbon assimilation rate is also modulated by a water stress factor and decreases in case of drought. It is hampered if insufficient nitrogen is available to maintain fixed N/C ratios. Temperature and radiation, which affect carbon assimilation rate, are reduced with the presence of shade trees. Water and nutrients availability are also modified through the coffee/tree competition for both resources.

Fractions of carbon allocated to coffee leaves, woody parts, roots and fruits are calculated from the sink strength of each organ (fig. 6). Woody parts, leaves and roots sink strengths are fixed as parameters in the model. However, roots sink strength is modulated by a water stress factor (TranF) and increases in case of drought. Leaves sink strength is enhanced during first weeks of reproductive growth. To reproduce the effect of competition for carbon between fruits and leaves, fruit sink strength is calculated taking into account coffee Leaf Area Index.

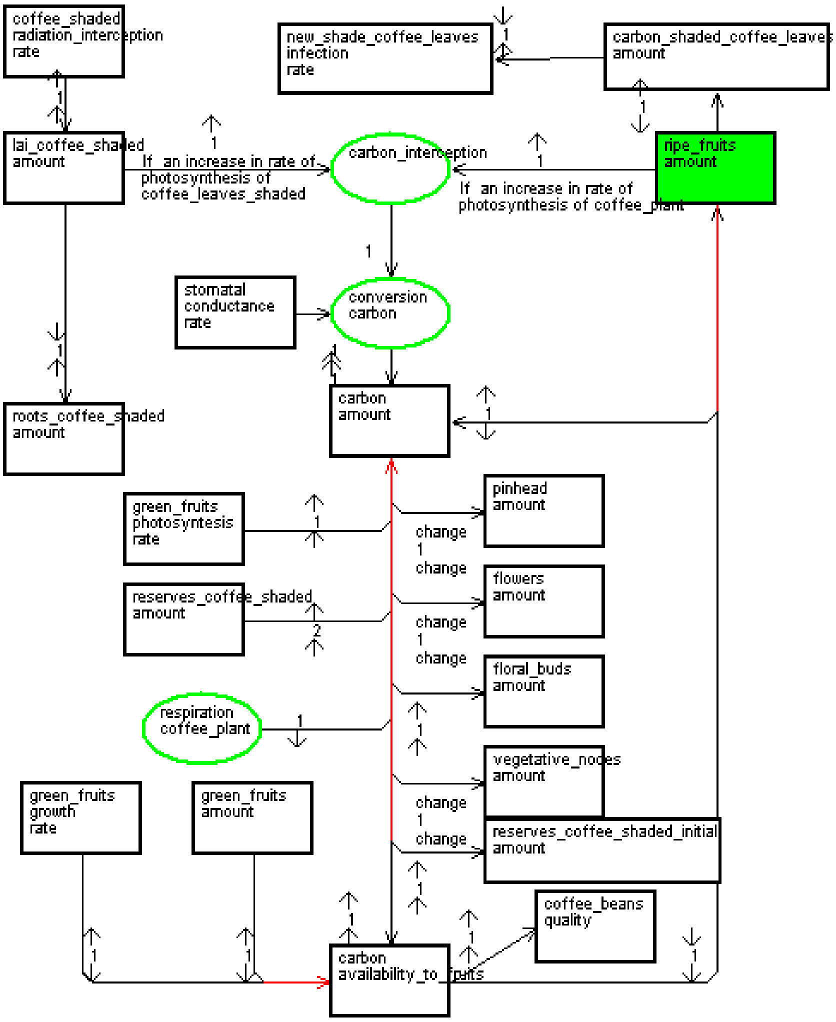

Figure 5: Carbon conversion and allocation diagram, academic source (Rebolledo, 2008)

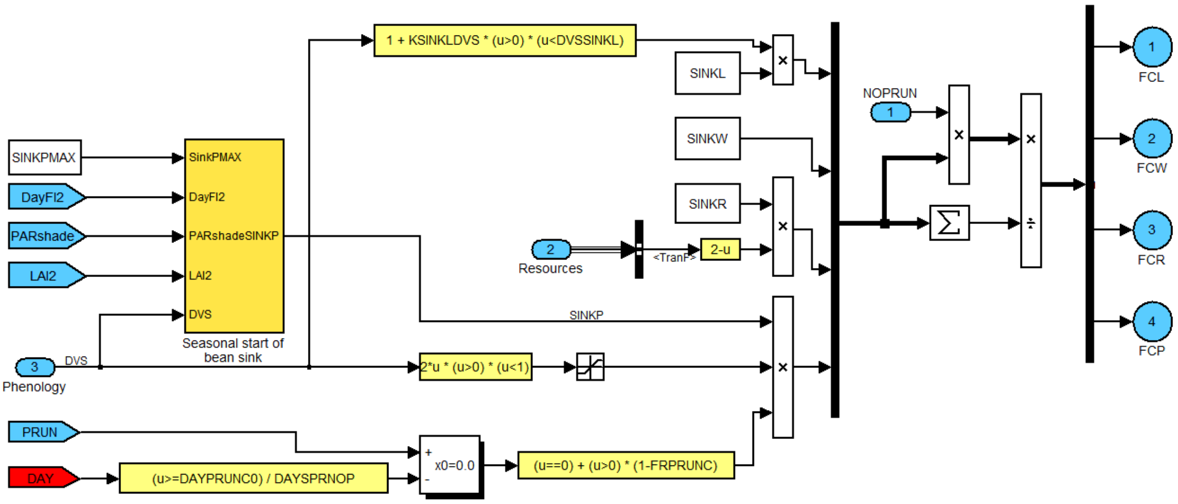

Figure 6: Scheme of calculation of coffee leaves, woody parts, roots and fruits sink strengths (respectively SINKL, SINKW, SINKR, SINKP) and their respective fractions of carbon allocation (FCL, FCW, FCR, FCP) in CAF2007. White boxes are fixed parameters given as inputs, blue boxes are inputs coming from other subsystems, and yellow boxes are calculations.

These implementations reflect the seasonal pattern mentioned above. Moreover, productive bi-annual pattern resulting from carbon competition between leaves and fruits is also implemented in CAF2007 by activating four parameters. Three of them are involved in the calculation of both leaves and fruits sink strengths and one in the calculation of leaves senescence rate in function of fruit growth rate. However, reserves dynamic are not taken into account in CAF2007, neither effect of fruit sink strength on carbon assimilation rate.

In all the other numeric models, light interception is also computed by Beer's law with some differences in the architectural design. Potential carbon growth rate is also function of environmental factors (radiation and temperature) and limited by water and nitrogen availability. Nevertheless, in the other models, it also depends on the phenologoical stages. In CAF2007, carbon growth rate is calculated independently from phenological stages; assimilated carbon is allocated in each organ, adding fruits after flowering activation. In APES, contrary to other models, effects of diseases and non biotic factors such as wind and froze on growth rate can also be simulated. Carbon is allocated to the different organs at each phenological stage according to allocations tables, which differs from CAF2007 where fractions are calculated from organs sink strengths.

Although the model seems to well describe carbon production and allocation, taking into account fruits/ leaves competition and effects of shade trees, the fact that some processes involved, such as reserves dynamics, are not implemented in CAF2007 can lead to problems to simulate the bi-annuality of coffee yields and trade-off and between productivity and longevity of coffee plantations. Moreover, shade trees can have large effects on all these processes by modifying coffee plants microclimate. Thus, it could be interesting to confront the processes of carbon biomass production and allocation under sun and different shade trees species against experimental data.

c- Coffee agroforestry systems water dynamics

The amount of water available for coffee plants development depends on: (i) rain amount and atmospheric humidity (the sources), (ii) the different uses of this water in plants' transpiration, soil evaporation, drainage and runoff (the sinks).

In Central America, two seasons are defined: a dry and a rainy season. The dry season which causes a drop in soil water is necessary to induce coffee flowering that is then activated by rain (Carr, 2001). However, if this season is too long, it can result in lower coffee production (Coste, 1968). In contrast, a better soil water status resulting from higher amount of rain increases the coffee water status. However higher temperature, radiation and wind speed lead to higher coffee transpiration rate, decreasing coffee water status (Rebolledo, 2008). Atmospheric humidity also influences coffee growth. In fact, stomatal limitations are induced by higher leaf temperature and vapor pressure deficit during the dry season, resulting in decreased coffee transpiration and photosynthetic activity (Carr, 2001; Coste, 1968). Moreover water dynamics impact on coffee beans yields and quality; bean size as well as fruit growth can be increased by improved soil water status and the need for irrigation varies depending on the rainfall distribution, the severity of the dry season, and soil type and depth (Carr 2001).

Many effects of shade trees on coffee agroforestry systems water dynamics have been reported. The presence of shade trees buffers microclimatic conditions and is assumed to reduce coffee water stress (Rebolledo, 2008) although in cases of more arid climatic conditions, it can increase this stress through water competition between coffee and tree (van Kanten and Vaast, 2006; Coste 1968). In a study made in 4-year-old coffee agroforestry systems in sub-optimal ecological conditions of Costa Rica, the presence of three shade trees species (*Eucalyptus deglupa*, *Terminalia ivorensis* and *Erythrina poepiggiana*) improved water status of the coffee plant although it also increases the total water consumption of the system (van Kanten and Vaast, 2006). Measured transpiration rates of coffee and shade trees appeared to follow the seasonal pattern and to depend on vapor pressure more than on photosynthetic photon flux density and potential evapo-transpiration. In fact, during the dry period, higher vapor pressure deficit limited coffee transpiration. Water flows are also modified by the introduction of shade trees in coffee plantations. Agroforestry systems displayed smaller total annual throughfall and larger annual stemflow compared to monoculture (Siles et al. submitted). Authors also show that with shade tree inclusion, the total rainfall interception was larger than in monoculture as a result of larger canopy storage capacity and surface of evaporation in agroforestry than in monoculture.

According to those studies, the first important point to underline is that coffee plants are not only sensitive to soil humidity but also very sensitive to atmospheric humidity (van Kanten and Vaast, 2006; Carr, 2001). Thus, we can wonder if both type of water stress experienced by coffee leaves and roots are implemented in CAF2007. Moreover, the presence of shade trees modifies systems' total evapo-transpiration but also soil water infiltration, drainage and run-off, so that it can be interesting to see in which conditions a better soil and coffee water status can be improved or not by the presence of shade trees in the model.

In CAF2007, two processes are simulated to characterize soil water status; soil evaporation, plants transpiration, drainage and run-off. Water sharing depends on coffee and tree demand (potential transpiration), on soil water availability and on water stress sensibility of both species. CAF2007 gives an important place to systems' water dynamics for coffee yields elaboration. In fact, the ratio of current transpiration of the plant to its potential one (TranF) is a water stress factor very often used in the model. It is used to calculate coffee LAI, roots growth rate but also leaves senescence. Water dynamics are described in two main subsystems of the model; the belowground resources subsystem where current soil evaporation and transpiration rate coffee and tree are calculated and the soil subsystem in which runoff and drainage are simulated.

The potential evapo-transpiration rate is computed for coffee and tree following Penman equation in function of climatic variables (temperature, wind speed, vapor pressure, radiation and rain) and LAI which is used to calculate amount of rain intercepted by the plant. The intercepted water reduces transpiration demand and evaporates the same day. Although the Penman-Montheith equation permits to take into account stomatal conductance to calculate reference evapo-transpiration rate, it has not been chosen in CAF2007 because of the unreliability of results obtained during model's building (Marcel van Oijen, personal communication). Nevertheless, this implementation is in contradiction with literature which underlines that coffee transpiration rate is also affected by water stress perceived not only by coffee roots but also by coffee leaves. Then, actual coffee and tree evapo-transpiration rates are deduced from potential ones, modulated by water availability into soil depth explored by coffee roots and a parameter that represents plant' sensibility to drought. Thus the water stress factor TranF only takes into account water stress perceived by coffee roots.

Runoff is modeled proportional to the daily rain not intercepted by the canopy, increasing from zero on flat soil to complete run-off on vertical soil. Run-off also decreases with higher total LAI, which describes the reduction of rain falling impacts on surface run-off in agroforestry systems. Drainage is calculated as the last term of water balance (i.e. soil water content plus rain minus water losses by evapo-transpiration, interception and run-off) and thus is also reduce by the presence of shade trees. Nevertheless, it is well known that both processes also involve soil's characteristics such as texture, porosity, hydraulic conductivity and depth (Roupsard Olivier, personal communication). However in CAF2007, it was a choice to keep the soil as a simple one-layer model of fixed depth to avoid lack of information on those parameters (van Oijen et al., submitted).

In the model WaNuLCAs, water dynamics implementation is more complex. The soil is described in two dimensions and composed of 16 compartments according to depth and distance to coffee plants and shade trees. The sharing is based on roots density, demand and supply by diffusion. Potential water absorption of each plant is calculated based on matrix flux for given roots density and soil water content. The model Hi-sAFe also integrates spatial heterogeneity of hydraulic soil conditions by roots voxels (3D). Water sharing is based on demand calculated with Penman-Monteith equation for tree and with K-ETP equation for the crops. Competition is than based on matrix flux taking into account roots lengths. Vertical flows are derived from the model STICS for water infiltration, evaporation and drainage. Run-off is a constant proportion of rain amount.

In APES four processes are implemented to describe soil water status: water distribution into the soil, soil evaporation, plants absorption and soil cultural practices. Soil depth is taken into account with parameters to describe hydraulic properties. The amount of water absorbed at each layer by each species is function of plants demand, soil description and roots distribution in the different layers. Water sharing is the same as in the model Hi-sAFe.

By comparison, water dynamics seem to be computed in a more simple way in CAF2007, without taking into account stomatal conductance to simulate plants transpiration, soil and roots spatial heterogeneity to simulate horizontal and vertical flows. Thus, subsystems involved in water dynamics in CAF2007 should be further tested as they can have important influences on the other connected subsystems.

d- *Coffee agroforestry systems nitrogen dynamics*

Finally, coffee agroforestry systems’ nitrogen dynamics are also investigated as a competition for this resource can appear between involved species, resulting in lower coffee productivity. Coffee is a crop very sensitive to nitrogen fertilization (Harmand et al. 2007) and it has been shown that in organic systems, yields are lower because of a lack of N-fertilization (Elias de Melo and Jeremy Haggar, personal communication). Moreover, a good N-nutrition enhances coffee carbon assimilation rate, resulting in increased vegetative growth and so in coffee productivity the following year (Rebolledo, 2008).

In Central America, coffee is very often over fertilized (Hergoualc’h et al., 2008; Van Oijen, submitted) which leads to overproduction. Moreover, filtering soils reduce fertilization efficiency by increasing losses by leaching. Thus, nitrogen fertilization also creates a risk of water contamination through nitrate-leaching. Introduction of shade trees in coffee plantations may increase N-accumulation in litter and permanent biomass and so limit this risk from excessive fertilization (Harmand et al. 2007).

N-fixing shade trees species also provide nitrogen through atmospheric N-fixation (Perrin et Remal, 2009). However pruning and fertilization are practices that contribute to reduce the N-fixation capacity of the shade trees (Rebolledo, 2008; Perrin and Remal, 2009). The presence of N_2 fixing shade trees, as well as the addition of nitrogen fertilizers, can increase N_20 emissions, because of the higher nitrogen inputs in litter and potential nitrogen soil mineralization rate (Hergoualc’h at al., 2008).

Based on these observations, we can wonder if CAF2007 can reproduce coffee sensitivity to nitrogen fertilization, shade trees effects on nitrogen recycling and fixation, and if this recycling allows a better nitrogen efficiency.

In CAF2007, nitrogen dynamics are implemented in two main subsystems: the soil subsystem to simulate nitrogen mineralization and the belowground resources subsystem to calculate nitrogen supply for both species (appendix 1). The soil C and N resource subsystem is composed of a single chain of decomposition of materials that contain both C and N. The chain consists of four subsystems representing four different soil pools: litter, fast degrading soil organic matter, slowly degrading, and mineralized material. In each pool, degradation of added carbon material (coming from coffee/tree pruning, thinning, organs senescence, or degradation of previous pool) is calculated with a fixed turn-over. Then, daily degraded carbon material is split with fixed ratios between respiration and degradation in the next pool (respectively 25% and 75% for litter, and 97% and 3% for fast degrading soil organic matter). The model keeps track of the amounts of C and N in the different pools. The decomposition steps for both elements are linked: in each pool, the rate of N degraded depends on the rate of C degraded.

N-uptake is then limited by either demand from the plants or supply from the soil. The N-supply follows a Michaelis-Menten function of soil mineral N concentration and is proportional to roots biomass. N-demand is the sum of organ-specific multiplications of N/C ratios with carbon growth rates.

The facts that in CAF2007 the N and C mineralization rates of soil organic matter do not take into account soil temperature and moisture, that the relative losses of C and N in soil compartment are assumed equal, and that every removed biomass from coffee/tree pruning and thinning are re-integrated to the soil and not exported for timber or firewood can be controversial. Moreover, soil N-mineralization and N-allocation in the different plants' organs are also strongly governed by C dynamics through the use of organs-specific N/C ratios for which information is limited (van Oijen et al., submitted).

The fact that nitrogen sharing of between both species depends on relative demand, relative roots density and on uptake capacity of both species, is common for all numeric models. Nevertheless, while in CAF2007 soil is represented as a unique layer with two compartments: shaded or not, in Hi-sAFe, soil is 3-dimensional and in WaNulCAS 2-dimensional. In the other models, potential uptakes are also function of diffusion speed from soil to roots, adding that in WanulCAS, this potential uptake cannot be superior to the one in monoculture. Thus, the Michaelis-Menten equation for N-supply calculation is specific to CAF2007. Moreover, in WaNulcas, biologic fixation is also included and demand is calculated from an empirical relation between absorption and biomass production in non-limiting condition. In Hi-sAFe and APES, demand is calculated according to optimal quantity in the different crops' organs. So, the calculation of demand based on carbon growth rates is also specific to CAF2007. All these specificities in implementation of N relations in CAF2007 should be further numerically tested for their impacts on productivity and environment.

e- Conclusion

Each of the four processes has been replaced in the conceptual models elaborated by Maria Rebolledo in 2008, in the conceptual schemes of CAF2007 but also of the other numeric models to underline similarities and differences. We chose those processes because performance of agroforestry systems depends on the interactions between tree and annual or perennial crop and more particularly on the competition for resources between both. All the compared numerical models simulate biophysical evolution of agroforestry systems, taking into account their characteristics and insisting on these interactions. However, the sharing processes of the above (light) and the belowground (nutrients and water) resources, are the most important but difficult to implement (Malézieux et al., 2009). Moreover, because coffee is a perennial crop, those interactions have to be considered in long-time period for coffee agroforestry system. That is why we conducted the conceptual evaluation having a particular interest for the implementation of those interactions in CAF2007.
As a result, we found that:

- Coffee phenology implementation in CAF2007 is not function of thermal time but is more specific to coffee with two key phonological events: flowering activation and fruits maturation. Flowering is activated by a fixed amount of rain, and its intensity depends on radiation. However, water and temperature stress are not taken into account for the calculation of coffee flowering activation and intensity.
- Coffee carbon production is simulated taking into account all the factors cited in the literature except effect of fruit load which explains the buffering effect of shade trees on productive bi-annual pattern. Implementation of carbon allocation in organs is not based on allocation tables and is kept simpler than in reality. Nevertheless, the competition between vegetative and reproductive growth during season can be activated in the model with a specific set of parameters.
- Water relations are also implemented in a simpler way than the reality and than in the other numerical models (soil is represented as a homogeneous layer), without taking into account stomatal conductance, though it is important to determine coffee water consumption.
- Nitrogen relations are also kept simple compared to reality and other numeric models. Soil is decomposed in 4 pools of organic matter degradation, which is calculated based on fixed turn-over for each pool ignoring effect of soil temperature and moisture. N-dynamics are also strongly related to C-dynamics which supposes that N/C ratios in coffee plants are maintained constant, which is an important assumption of the model.

Table presented in appendix 4 recapitulates the four processes we identified that should be tested numerically, the subsystems involved in each process in CAF2007, the ideal set of data needed to test the process and the name of parameters involved in each one. To test those processes, it would be interesting to disconnect each subsystems involved in CAF2007 to avoid the other effects caused by the numerous links existing between variables and parameters which may reduce the efficiency of an evaluation. However, those modules are not easy to disconnect, and needed data set for testing were not available. Thus, it has not been possible yet to test those processes numerically and a global numerical evaluation of the model has been performed.

2- Numerical evaluation of CAF2007

A - Data collect

Climatic data

Climatic data were easy to collect from Turrialba trial as a meteorological station is located and managed by CATIE. However, for Masatepe, only 2,8 years of radiation were available. Missing-years data were generated based on the empirical distribution of available time series with the software Infostat and the statistic Fisher test was performed to ensure the variances equality between years (p-value>0,05).

Model initialization

Determination of initial state variables for coffee and tree was not possible as they have not been measured at the establishment of experiments so that we kept working with the default data. However, in Masatepe we measured the carbon content in shade trees organs biomass from five plants collected in a nursery at the stage of implantation. The plants were dried and the different parts were then weighted separately.

The table of all parameters values for the model initialisation is presented in appendix 5. For each treatment the values obtained are mean of their three replicates. Initial state variables for soil were determined from data sets coming from studies in both sites.

Management

The management parameters are also included. Coffee is assumed to reach its full productivity the third year after its plantation and to necessitate one year to reach this productivity after being pruned. First coffee pruning is done earlier in Turrialba than in Masatepe. This could be explained by the arid climate in Masatepe, which contributes to slow down the growth. In both site, coffee is pruned each year after harvest. The fraction of biomass which is pruned varies each year according to the potential productivity of each plant. However, the model takes into account the same rate for each year. Thus, we calculated the mean for this fraction among years which has been found higher in Turrialba than in Costa Rica.

Management of shade trees depends on the species. In Turrialba, *Erythrina poepiggiana* is pruned twice a year since the first year while the first pruning of *Terminalia amazonia* happened only the sixth year. Fraction of pruned biomass was assumed to be 20% higher for IC treatment than for MC treatment with *Erythrina* while equal in both treatments with *Terminalia*. In Masatepe, *Inga glauca* has been pruned since the fifth year and the fraction of pruned biomass assumed to be equal in both treatments. Two tree thinning has been done recently two times in both sites at a rate of 50%.

N-fertilizers are applied three times a year in both sites at a rate of 300 kgN/ha/year for the intensive conventional treatment and at a rate of 150 kgN/ha/year for the medio conventional treatment.

Coffee yields

Coffee annual yields have been collected for the three replicates of each subplot, averages are presented in Table 6 for each subplot. In the figure 7, we plotted those yields for each treatment. Coffee yields are generally higher with the intensive conventional management than with the moderate one. This confirms the above mentioned sensitivity of coffee for N-fertilization.

Table 6: Observed coffee annual yields (tDM/ha/y) in Turrialba and Masatepe

	Masatepe				Turrialba					
	Full Sun		*Inga*		Full Sun		*Erythrina*		*Terminalia*	
year	IC	MC	IC	MC	IC	MC	IC	MC	IC	MC
2000	0	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0,47	0,68	0,36	0,17	0,29	0,09
2003	0,24	0,26	0,10	0,07	2,77	2,30	2,27	1,56	2,09	1,78
2004	1,10	0,37	0,47	0,60	0,80	0,70	1,05	0,74	1,03	0,51
2005	1,60	0,58	1,02	0,58	2,45	2,00	2,21	1,58	2,38	1,83
2006	1,99	1,69	1,23	1,14	0,88	0,42	0,75	0,10	0,34	0,13
2007	1,09	1,06	0,93	0,72	2,74	2,72	2,32	1,26	1,56	1,54
2008	0,85	0,50	0,65	0,33	0,91	0,50	1,21	0,67	0,46	0,31
Mean	**0,76**	**0,50**	**0,49**	**0,38**	**1,23**	**1,04**	**1,13**	**0,68**	**0,91**	**0,69**

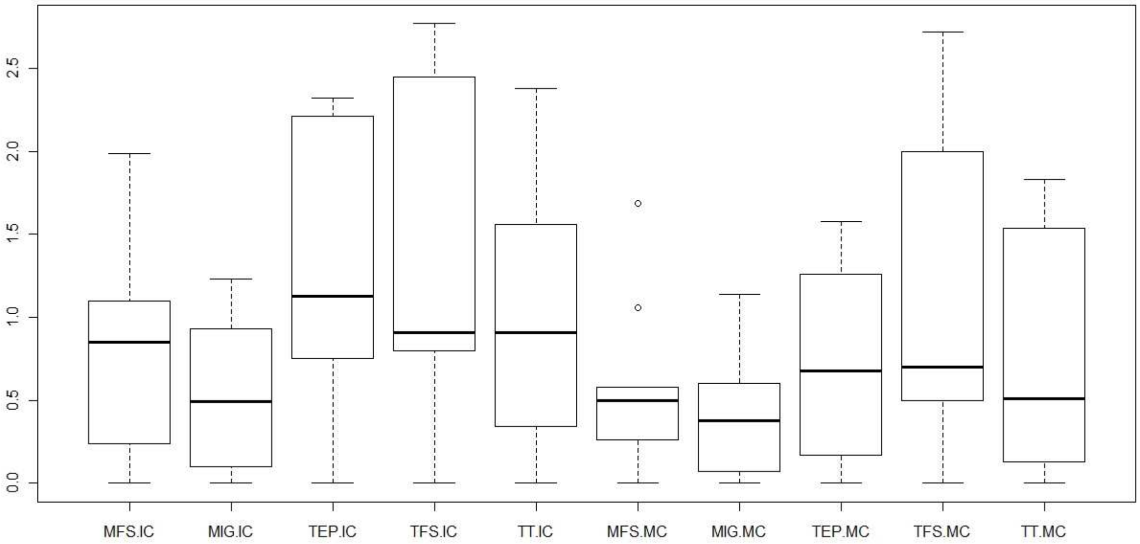

Figure 7: Boxplot of observed yields in function of the treatment.
M: Masatepe, T: Turrialba, FS: Full Sun, IG: *Inga laurina*, EP: *Erythrina poepiggiana*, TT: Turrialba-*Terminalia amazonia*, IC: Intensive Conventional, MC: Moderate Conventional.

We also represented the interaction between level of inputs and subplot in figure 8.
As a result, we can see that:

- Coffee yields are higher with a higher level of fertilization, but also that
- Coffee yields are higher under full sun than under shade.
- Coffee yields are higher in Turrialba than in Masatepe, where arid climatic conditions are less favorable for coffee production.

We then performed a multi-factorial analysis of variances with the statistics software R and found that there were no significativity of the interaction between the inputs level, the subplot and the year to explain coffee yields (p-val>0,05). That means that there is no simultaneous effect of these three factors on coffee yields. Thus, we then test the effect of each factor and found that coffee yields variation is not explained by the level of inputs (p-val>0,05), but more by the subplot and by the year (p-val<0,05). Although it has been reported that coffee is sensitive to fertilization, in this study we couldn’t confirm statistically this hypothesis. In fact, the presence and type of shade tree species and climatic conditions are more likely to explain variability of coffee productivity.

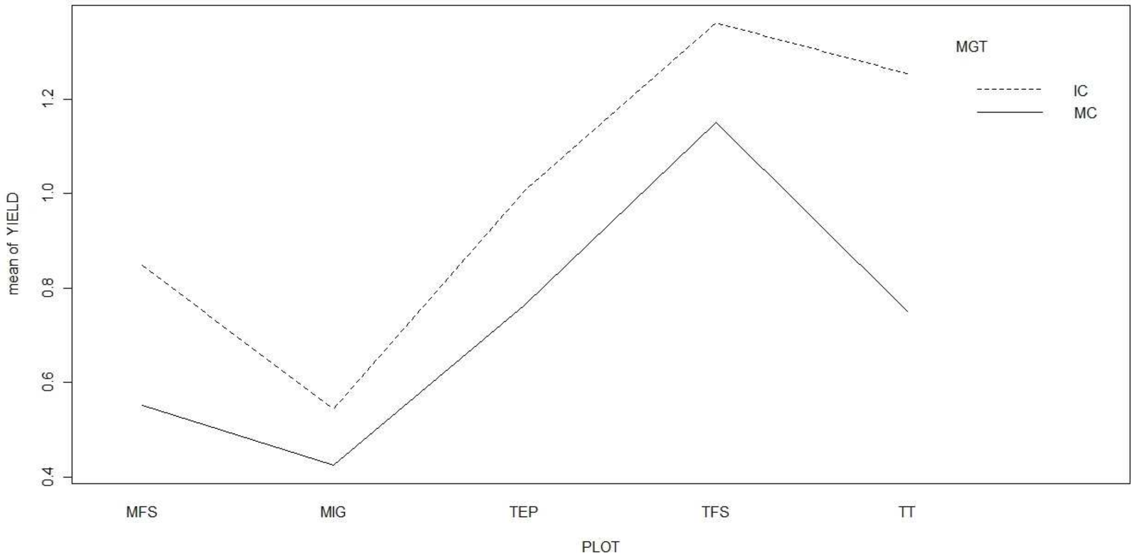

Figure 8: Graphic representing mean of yields in function of interaction between the level of input (MGT) and the subplot on abscissa (PLOT).

Finally, we plotted coffee yields obtained in each subplot in function of years (fig. 9 and 10). While in Turrialba, the bi-annual pattern of coffee productivity, mentioned in literature, is well defined, in Masatepe, it is not. This can be explained because in Masatepe yields are generally lower (p-val<0,05), and thus the effect of competition for carbon between vegetative and reproductive growth is less pronounced.

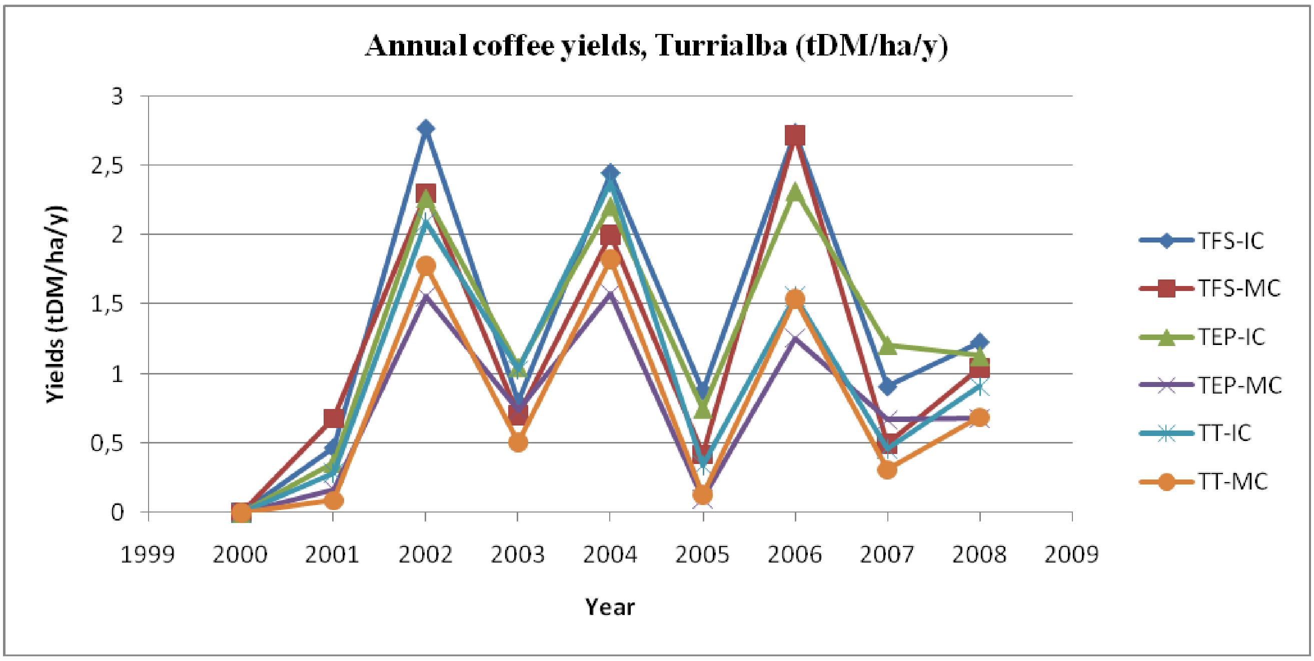

Figure 9: Annual coffee yields in Turrialba.
IC: Intensive Conventional, MC: Moderate Conventional, TFS: Turrialba-Full Sun, TEP: Turrialba-*Erythrina poepiggiana*, TT: Turrialba, *Terminalia amazonia*.

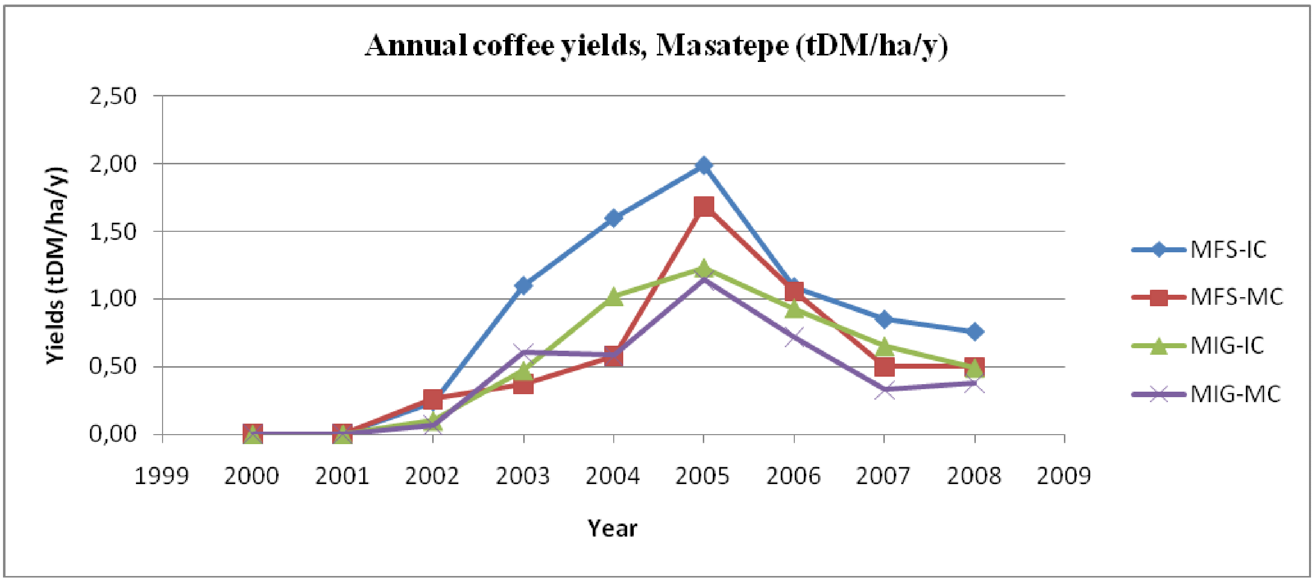

Figure 10: Annual coffee yields in Masatepe
MFS: Masatepe-Full Sun, MIG: Masatepe-*Inga laurina*, IC: Intensive Conventional, MC: Moderate Conventional, MFS

Moreover, in Turrialba, yields are higher under *Erythrina* than *Terminalia* with the intensive conventional management. This can be explained by the N-fixing capacity of Erythrina. However for the moderate conventional management, decreased coffee yields are not different under both species, underlying that N-fixation by *Erythrina* was not sufficient to contribute to increase yields. This might be explained because in the moderate conventional treatment, *Erythrina* was pruned twice per year to remove some branches so as to provide a constant shade, possibly reducing coffee production when shade cover was high. This is contrary to the traditional management of pollarding the tree twice per year removing all branches, which was implemented for the intensive conventional treatment. With this type of management, shade is more reduced at important coffee stages of yields elaboration (before flowering to increase flowering intensity and after to increase fruits growth). In Masatepe, *Inga* shade systems had lower coffee productivity compared to full sun systems. This can also be linked to higher shade levels during the dry season.

Measurement of Specific Leaf Area

Specific Leaf Area (SLA) is used in the model to calculate LAI from leaves carbon biomass. We measured this parameter for coffee and the three shade trees species involved in the chosen subplots. Results are shown in table 7.

For coffee, the maximum specific leaf area was obtained for leaves collected under shade and the minimum for leaves collected under full sun. The observed difference of SLA between shade and full sun systems can be due to the fact that under shade, leaf area is more extended in order to increase light interception compared to full sun system (data not shown). Also under full sun, SLA was found higher for young leaves than mature and old ones and under shade, however no differences were observed between leaves age under shade (data not shown).

Compared to default data included in the model from literature review, both measured coffee SLAMAX and FSLAMIN were quite similar. Nevertheless, thanks to these measurements, we could adjust values of SLA for *Terminalia* and *Inga*, as default data were higher than measurements. This could be because except for *Erythrina poepiggiana*, species included in the model are different from those in both trials even though from the same gender.

Table 7: Measured Specific Leaf Area and default data included in CAF2007

Parameter	measured data	default data
SLAMAX_*Coffea* (m2/kg C)	27,61	27
FSLAMIN_*Coffea* (-)	0,68	0,64
SLAT _*Erythrina* (m2/kg C)	38,82	38
SLAT _*Terminalia* (m2/kg C)	18,16	32
SLAT_*Inga* (m2/kg C)	26,15	39

B - Sensitivity analysis of CAF2007

We performed the sensitivity analysis to have an idea of sensitivity of model's responses to inputs' uncertainty. Coefficients of variations obtained for each parameter for each of the 7 chosen outputs are shown in Table 1, 2, 3 and 4 of appendix 6. If read in line, these tables give information on the parameters that have influence on each output while when read in column, they give an idea of the most sensitive outputs to the uncertainty of a given parameter.

CAF2007 seems not to be sensitive to initial state values for coffee and tree, which is an advantage because those values are not often available. However, uncertainty of initial state values for the soil compartment affects more the different outputs, meaning that those values have to be well entered in the model to interpret model's response (tab. 1, appendix 6).

The two outputs which are the most sensitive to variation of tree parameters are the tree wood volume and the carbon sequestration (tab. 2, appendix 6). In fact, all the parameters used to simulate tree growth and allocation into the woody parts, have an influence on tree wood volume, as well as on carbon sequestration because in the model pruned and thinned tree material is degraded into the soil.

Coffee yield, soil carbon sequestration and run-off are the three outputs which vary the most when we vary coffee parameters (tab. 3, appendix 6). Coffee yield is relatively more sensitive to parameters used to calculate coffee carbon production and allocation into the different organs. Carbon sequestration is sensitive to parameters affecting coffee growth rates and allocation into organs which are not exported. Nevertheless, the fact that it is less sensitive to woody part carbon sink strength was not expected. Run-off is also sensitive to coffee parameters which are involved in the calculation of LAI. Drainage, tree wood, N-leaching and N-emission are relatively less sensitive to coffee parameters.

Except drainage, all the outputs are very sensitive to soil parameters (tab. 4, appendix 6). Fraction of soil water content at field capacity has a great influence on all the outputs. This can be explained as it is used to calculate water dynamics in the systems. For the same reason, fraction of soil water content at wilting point also impacts on different outputs. Efficiency of organic matter degradation, time constant for unstable organic matter decomposition, ratio of runoff in bulk soil are also important parameters for all outputs. Gaseous N-emission, N-leaching and run-off are also governed by parameters specific to their calculation.

This analysis also permits to select important parameters that need to be further well calibrated as having more important impacts on the model outputs (Makowski et al. 2006). Those parameters are those with high coefficients of variation values for several outputs. In the other way, uncertainty of some parameters has very low impact on these outputs and thus need less to be accurately determined.

C – Numerical evaluation of CAF2007

To do the numerical evaluation of CAF2007, we first run the model with the default settings of parameters (appendix 3). Then, we run the model with collected data for soil, management for each subplot (see appendix 4). Obtained simulated coffee annual yields were compared with observed ones for both modeling situations and relative root mean square errors were calculated (tab. 8). Table 9 presents averages of RRMSE calculated according to different factors: localization, level of inputs, crossing of localization/level of inputs and type of combination.

Table 8: Relative roots mean square errors calculated for each subplot, in both modeling situations: model with default setting of parameters (DEF) and model with measured initial state and management variables and Specific Leaf Area (MES).

SUBPLOT	RRMSE- DEF	RRMSE- MES
T-MC-EP	1,1985	0,6223
T-MC-TA	1,0977	0,9666
T-MC-FS	1,3458	0,9657
T-IC-EP	0,8657	0,4799
T-IC-TA	1,0300	0,9068
T-IC-FS	1,0658	0,6780
M-MC-IL	1,8535	2,1847
M-MC-FS	1,6549	1,4601
M-IC-IL	1,6770	1,7161
M-IC-FS	1,2419	0,6183

T: Turrialba, M: Masatepe, MC: Moderate conventional, IC: Intensive Conventional, EP : *Erythrina poepiggiana*, TA : *Terminalia amazonia*, IL: *Inga laurina*, FS: Full sun.

Table 9: Average of RRMSE calculated for both situations, for different factors: the localization, level of inputs, crossing of localization/level of inputs, type of combination.

FACTOR	RRMSE- DEF	RRMSE- MES
T	1,1006	0,7699
M	1,6068	1,4948
MC	1,4301	1,2399
IC	1,1761	0,8798
T-MC	1,2140	0,8515
T-IC	0,9479	0,6934
M-MC	1,7542	1,8224
M-IC	1,4594	1,1672
EP	1,0321	0,5511
TA	1,0639	0,9367
IL	1,7653	1,9504
M-FS	1,4484	1,0392
T-FS	1,2058	0,8219
FS	1,3271	0,9305

T: Turrialba, M: Masatepe, MC: Moderate conventional, IC: Intensive Conventional, EP : *Erythrina poepiggiana*, TA : *Terminalia amazonia*, IL: *Inga laurina*, FS: Full sun.

In figures 1 to 5 of appendix 7, we plotted observed coffee annual yields and simulated one for each combination for both modeling situations. These plots first reveal that with the default settings of inputs, simulated yields become very low the third productive year. This can be explained because in this simulation coffee is drastically pruned every five years although it is really pruned annually since the first year after plantation. This contributes to explain the higher values of RRMSE obtained for this modeling situation compared with those obtained for simulations with collected data (tab. 8 and 9).

Except in Masatepe under *Inga laurina*, running the model with collected data gives lower differences between observed and simulated yields and thus lower values of RRMSE than running the model with default settings of inputs in all combinations (fig. 11 and tab. 9). Thus, variables of management and initial soil carbon and nitrogen composition need to be well implemented in the model to give better predictions. Nevertheless, implementation of management stays simpler in the model than in reality. In fact, each coffee plant is pruned annually after harvesting with a variable intensity function of its productivity the previous year, while in the model fraction of pruned biomass stays constant among years.

The bi-annual pattern of coffee yields observed in Turrialba is not reproduced by the model (fig. 1 to 3, appendix 7). This might be explained by the fact that pruning intensity is constant among years, as well as by the fact that reserves dynamics are not included in the model. Thus, the effect of pruning intensity on coffee plants production and reserves accumulation for the following year is ignored. The four parameters implemented to describe this bi-annual pattern has been activated but yields were found very low and thus RRMSE were very high (data not shown), suggesting that these parameters need to be more accurately calibrated to simulate the pattern.

Except in Turrialba with the shade tree species *Erythrina poepiggiana*, in all other combinations efficiency of N-fertilization is underestimated (fig. 1 to 5, appendix 7) by the model and values of RRMSE are higher with the moderate conventional level of N-fertilization than with the intensive level (tab.9). This suggest that implementation of N-relations in the model should be revised. However, the fact that effect of N-fertilization on simulated yields of coffee is better simulated under *Erythrina poepiggiana* also suggests that the model can be improved by a better calibration of shade trees parameters. In fact, the coffee agroforestry system involving *Erythrina poepiggiana* has been well documented compared to other species of the experiments (van Oijen et al., submitted). Moreover, the other shade trees species are not included in the model and we worked with species of the same gender, which can have led to a greater source of error and thus higher RRMSE values compared to those of *Erythrina poepiggiana* (fig. 11 and tab. 9). The species-specific parameters are related to C and N tree dynamics (see tab.4, appendix 3), so they can have an important influence on C and N soil recycling. Thus, before changing implementation of N-relations in the model, a calibration of shade tree species parameters should be performed.

In both modeling situations, RRMSE were found higher for Masatepe than for Turrialba (tab. 9). The model, run with collected data inputs in Masatepe, over-estimates coffee yields under full sun and under *Inga laurina* during the first productive years (fig. 4 and 5, appendix 7 and 8). In fact, implantation of coffee plants was difficult in Masatepe and it took some years for coffee plants to be well developed (Haggar Jeremy, personal communication) and this has not been reflected by simulations.

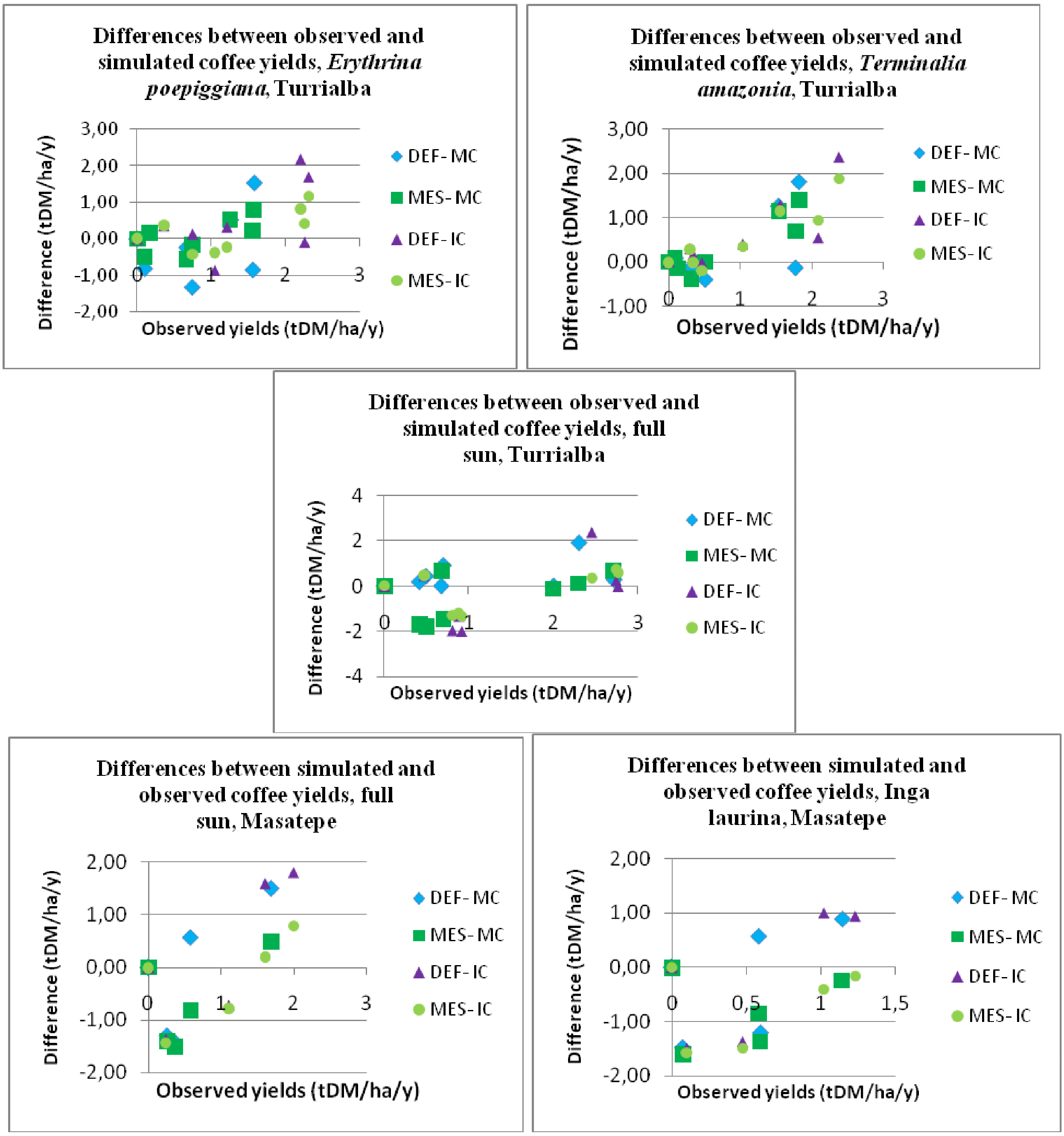

Figure 11: Differences between simulated and observed coffee yields for both modeling situations. DEF: model with default settings of inputs, MES: model with measured inputs, MC: Moderate conventional, IC: Intensive Conventional

This result also suggests that the model is more adapted for simulations of coffee agroforestry systems in humid zones than in arid ones with longer dry season. This can be due to the model simplicity for its implementation of water dynamics. Besides, the sensitivity analysis has shown the importance of soil parameters for calculation of final coffee bean annual yields, underlying that CAF2007 need at least to be well informed for these parameters values. Fraction of soil water content at field capacity, which has an influence on several outputs (appendix 6), depends on soil structure which varies among sites (Haggar, personal communication).

Moreover, the fact that the model doesn't take into account stomatal conductance to simulate plants' transpiration and photosynthetic activity, can contribute to explain the difference between both sites. In fact, through the conceptual evaluation, this factor has been shown to be important for calculation of water relations in coffee agroforestry systems. In Masatepe, climate is more arid than in Turrialba so that stomatal limitations of coffee growth might be more important than in Turrialba. Thus, by ignoring this process, CAF2007 might over-estimate yields in drier climatic conditions.

In appendix 8, we plotted simulated yields against observed yields and traced the line y=x for each treatment. Globally model under-estimates yields in Turrialba with a better prediction of coffee yields under full sun than under shade trees species (fig. 1 to 3 appendix 8). However RRMSE value is higher than under *Eryhthrina poepiggina* (tab. 9) because of the accentuated bi-annual pattern under full sun. By contrast, model over-estimates yields in Masatepe (fig 4 and 5, appendix 8) with higher values of RRMSE under Inga laurina than under full sun.

To conclude, we can say that model is more performing to simulate coffee agroforestry systems in Turrialba, under full sun and under the shade tree species *Erythrina poepiggiana*. This might be explained because model's parameters estimation from literature was more precise for those situations, suggesting that parameters should be calibrated more precisely. Moreover, the fact that simulations were closer to observations when model was run with collected initial values of C an N soil composition and management for each subplot suggests that this model needs site-specific inputs values.

IV- Conclusion and perspectives

To participate to continuation of CAF2007 elaboration, its conceptual evaluation was done, based on literature review and collected knowledge from experts on coffee agroforestry systems in Central America. We found the model simple, however specific to those systems, taking into account characteristics of coffee as a shade plant as well as interactions between coffee and tree. Nevertheless, some critical points can be improved in the model as they have been shown to be important to evaluate systems' productivity and environmental impacts. We advice to further test numerically four processes described by the model: coffee phenology, coffee carbon production and allocation, water and nitrogen dynamics in the systems. For this evaluation, subsystems need to be isolated in the model and data might be collected from two short-term experimentations in Costa Rica: Aquiares and Perez Celedon.

We then tested the model globally for it capacity to well simulate coffee productivity using data from two long-term experiments in two contrasted agro-ecological zones: Turrialba and Masatepe. From these experiments, we found that coffee yields were higher with a higher level of fertilization, and under full sun than under shade. Bi-annual pattern of coffee productivity was more pronounced in Turrialba than in Masatepe. Coffee productivity was also higher in Turrialba than in Masatepe, where arid climatic conditions are less favorable for coffee production. The presence and type of shade tree species and climatic conditions were more likely to explain variability of coffee productivity.

We calculated relative roots mean square error between observed and simulated coffee annual yields for two modeling situations: with default settings of inputs and with collected data from experiments. From this comparison, we show that CAF2007 needs site-specific values as inputs to give better predictions. Moreover, CAF200 seems to be more performing to simulate coffee agroforestry systems in humid tropical zones than in more arid ones. This confirms that the model needs to be more precisely tested for its implementation of systems' water dynamics. Moreover, efficiency of N-fertilization was under-estimated by the model. That also reveals that N-relations might also be improved in the model.

Lowest values of RRMSE were found for coffee production under full sun and *Erythrina poepiggiana*, suggesting that information on parameters for those two situations were more adequate. Nevertheless, CAF2007 doesn't reproduce bi-annual pattern of coffee productivity as it doesn't include neither reserves dynamics, neither year-specific management. Thus, the fact that overbearing exhausts coffee's reserves and limits the production of leaves, leading to poor crop the next year, which allows an excessive foliage to form which, in turn, permits an intensive flowering and hence a good yield (Da Matta et al., 2004), cannot be described by the model.

Finally, the high values of RRMSE found for other shade trees combinations as well as the sensitivity analysis also suggest that CAF2007 needs to be more precisely calibrated. Data have already been collected from both sites to perform automatic calibration through Bayesian method to quantify the model uncertainties (van Oijen et al., submitted). Parameters to include for this calibration can be selected according to three criteria: (i) from the literature review, (ii) the conceptual evaluation to select parameters which are involved in the four identified processes and (iii), from the sensitivity analysis which permits to screen important parameters from all the parameters set.

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