The use of plant architectural models for estimating radiation transfer within agroforestry systems-an example for multi-strata coconut-based farming systems

I. Mialet-Serra[1], J. Dauzat[2], D. Auclair[3]

Keywords: Intercropping, *Cocos nucifera*, *Theobroma cacao*, Computer mock-up.

Introduction

In many multi-strata agroforestry systems, transmitted photosynthetically active radiation (PAR) can be a limiting factor, particularly for the establishment and growth of annual intercrops. Knowledge of the radiative climate under a given stand according to age, planting density and planting pattern is therefore of major interest for the management of multi-strata coconut based farming systems.

The present paper describes the use of a series of software modules developed at the "AMAP" plant modelling laboratory for predicting radiative environment in various situations. Three-dimensional numeric mock-ups were computed according to the "AMAP" methodology (Reffye *et al.*, 1995). Average values and spatial distribution of transmitted PAR reaching the ground were then calculated and mapped under "virtual" coconut stands in different situations. After validation with field measurements, it was possible to predict the yield of annual crops (corn and mungbean) according to the estimated transmitted PAR. This method was then tested on cocoa perennial intercrops.

Materials and Methods

Plant material

Field experiments on coconut stands (*Cocos nucifera* L.) were conducted at three sites: Port-Bouet Station (Côte d'Ivoire), the Vanuatu Agricultural Research and Training Centre, and the Davao Research Centre of the Philippines Coconut Authority. Different treatments involved coconut age, variety, planting pattern and planting density (Table **1**).

Table 1. Plant material and planting design

	Variety	**Age (years)**	**Planting density (stems/ha)**	**Planting pattern**
Côte d'Ivoire	WAT x RLT*	16	115	Triangular (N-S)
		16	143	"
		16	180	"
Philippines	Laguna Tall	5	143	Triangular (N-S)
		20	143	"
		40	156	Square (N-S)
Vanuatu	VTT**	6	143	Triangular (N-S)
	VRD x VTT***	10	143	"

* WAT x RLT= West African Tall x Rennell Tall
** VTT= Vanuatu tall
*** VRD x VTT= Vanuatu red Dwarf x Vanuatu tall

---

[1] CIRAD-AMIS, programme agronomie
[2] CIRAD-AMIS, programme modélisation (AMAP)
[3] INRA / CIRAD, programme modélisation (AMAP)
B.P. 5035, 34032 Montpellier cedex 1, France

Description, modelling and simulation of coconut stands

Coconut follows the architectural model of Corner, as described by Hallé and Oldeman (1970). It is characterised by the existence of a single meristem with indeterminate growth, and the development of lateral fronds and inflorescences. Although its topology is quite simple, an accurate geometrical description was needed. This was obtained by measuring trunk height and diameter, projection, and azimuth, as well as some detailed frond characteristics: rachis length, leaflet number and surface area, inclination at the junction of petiole and rachis curvature, insertion angles. A data file including synthetic parameters and functions (means and standard deviations, power or quadratic functions) was used for each site to build three-dimensional numeric mock-ups through a specific coconut generator software (Dauzat and Eroy, 1997), taking in account the observed intra- and inter-tree variability.

Radiative climate measurements and simulation under coconut stands

In the field, the quantity of transmitted PAR was measured by a set of 32 quantum sensors placed at the soil level within the coconut stand. On the numeric plant mock-ups, specific modules (Dauzat and Eroy, 1997) make it possible to:

- calculate the interception of incident radiation by the coconut, and, if relevant, by the intercrop,
- map the spatial distribution of light reaching the ground,
- calculate the multiple scattering of intercepted light at different levels in the canopy,
- combine above results to obtain a total radiative balance.

Results

Radiation simulations

Transmitted PAR was simulated for the coconut stands described in Table 1. The daily evolution of PAR transmission was satisfactorily simulated (Figure 1). Simulations were in good agreement with field measurements for the different experimental designs (Figure 2). For a given age, PAR transmission was linearly related to coconut density, irrespective of planting pattern. For a given planting density, PAR transmission showed important variations according to age in relation with an increasing crown development from 5 to 15 years, and a gradual decrease after 20 years.

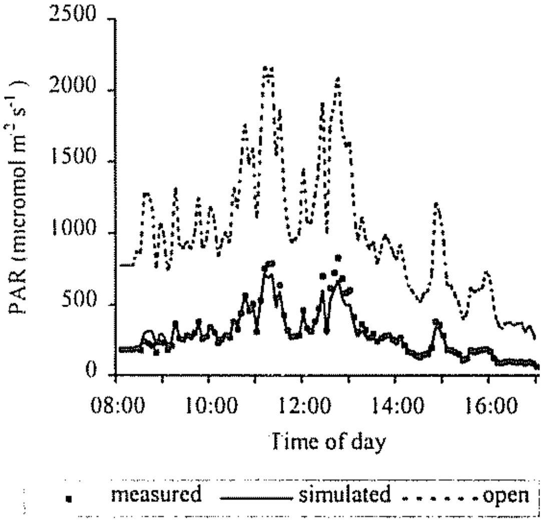

Figure 1. Example of daily evolution of the PAR transmitted under 10-year-old VRD * VTT coconuts at 143 stems/ha in Vanuatu and in the open.

Forecasting yield of annual intercrops

Dauzat and Eroy (1997) observed an almost linear response of crop yield to PAR for corn and for mungbean. In order to simulate the expected yields of the same annual crops grown in a multi-strata system, the above simulations were used to estimate PAR transmitted under coconuts. Intercrop yield was obtained by relating the field measurements at different PAR levels to the simulated PAR.

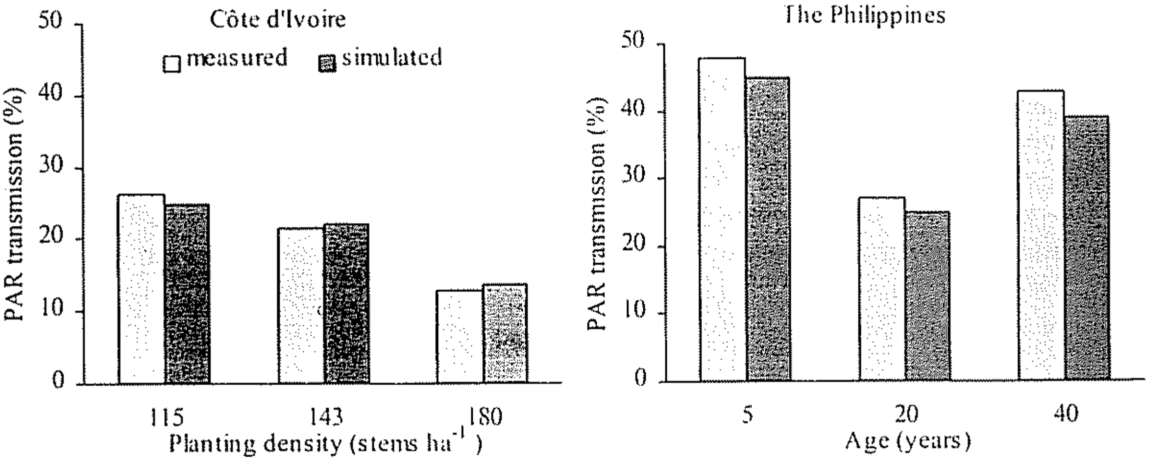

Figure 2 Comparison of simulated and measured PAR transmission under coconuts, according to planting density in Côte d'Ivoire (left) and to age in the Philippines (right)

It was thus possible to satisfactorily simulate experiments with different coconut densities, ages, and pruning intensities.

Radiation intercepted by a cocoa intercrop

In order to test this method on perennial intercrops, the architecture of *Theobroma cacao* L. was studied, and numeric mock-ups were computed according to the "AMAP" methodology (Mialet-Serra, 1998). Although the daily evolution of the transmitted PAR (Figure 3) under coconuts was different for clear (Diffuse/Global = 0.23) or overcast sky (Diffuse/Global = 1), the total daily transmitted radiation intercepted by cocoa was constant, irrespective of external radiative conditions.

A map of the spatial distribution of light reaching the ground was produced for a coconut-cocoa intercropping system (Figure 4), and according to the cocoa experimental design the intensity of light available for each tree was estimated. However, for a perennial crop such as cocoa, it was not possible to relate yield to the transmitted radiation as for annuals.

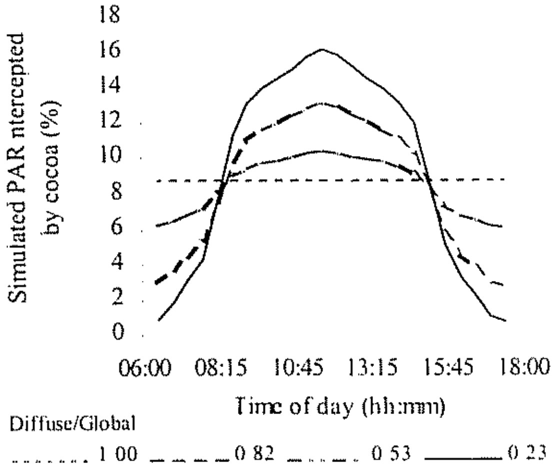

Figure 3. Simulated daily evolution of intercepted PAR by a *Theobroma cacao* stand in Vanuatu, according to external conditions.

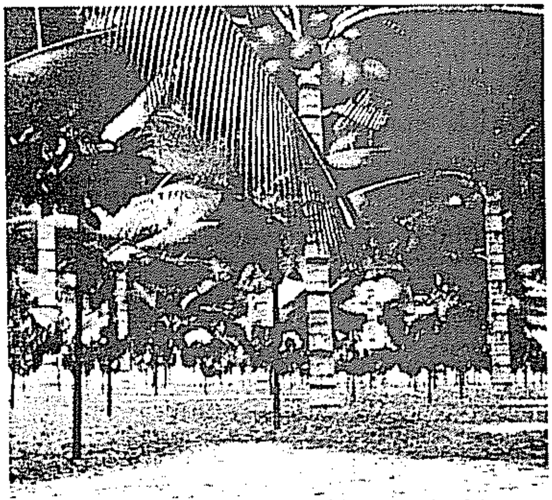

Figure 4 Computer-generated image of a 24-month-old cocoa intercrop under 6-year-old coconut in Vanuatu.

Discussion

Simulations of PAR transmission through a coconut canopy were validated at several sites for several varieties, and with various planting patterns and densities. A good agreement was obtained between the estimated PAR and field measurements. By using three-dimensional numerical mock-ups of coconut linked to the radiation calculation modules, transmitted radiation can thus be estimated accurately. In the absence of water deficit and nutrient competition, and considering PAR as the most important limiting factor, it was possible to predict yield of annual intercrops through this approach. We can now multiply "virtual" experiments in which age, planting density, planting pattern, and management practices can vary. Thus, it is possible to adapt management practices in a multi-strata system with annual intercrops according to the PAR requirement of the intercrop.

In the case of intercropping between coconut and cocoa, light is probably not the main limiting factor. Cocoa is a shade-tolerant perennial: leaf gas exchange is characterised by a low photosynthetic rate, and the maximum photosynthetic rate is reached for a low radiation (CIRAD-CP, 1998). Measurements in Vanuatu have shown highly heterogeneous net assimilation values, depending on the tree location and light environment (Bastide, 1996). The use of numeric computer mock-ups will help to improve the sampling techniques within the canopy of cocoa plants, with a view to developing process-based models.

Early results have shown that some architectural features of young cocoa can be influenced by the amount of shading, exhibiting differences between monoculture and intercropping conditions (Mialet-Serra, 1998). Further studies are now under way to link these architectural characteristics to light conditions. Branched and leafed entities of adult cocoa plants have been accurately described: their position within the canopy and growth dynamics have been recorded by integrating the chronology of formation of the branched structure. For yield predictions, the architectural development of the cocoa tree is probably more important than photosynthetic rate, and particularly the position of flowers and the development of fruit.

References

Bastide P (1996) Fonctionnement du cacaoyer, shéma d'élaboration du rendement en association. *In*: EC STD3-TS3-CT92-0132, 3rd technical report. 20 p.

CIRAD-CP (1998) Coconut-based farming systems - Operational and economic analysis models. *In*: EC STD3-TS3-CT92-0132, final report. CP n°944/98. 30 p.

Dauzat J and Eroy M (1997) Simulating light regime and intercrop yields in coconut based farming system. *European Journal of Agronomy* 7: 63-74

Hallé F and Oldeman RAA (1970) *Essai sur l'architecture et la dynamique de croissance des arbres tropicaux*. Collection de monographies de Botanique et de Biologie Végétale 6. Masson et Cie, Paris

Mialet-Serra I (1998) Preliminary study of aerial development in *Theobroma cacao* L. in a monoculture and intercropped with coconut. *In*: EC STD3-TS3-CT92-0132, Annexes, 8, CP n°944/98. 95 p.

Reffye (de) P, Houllier F, Blaise F, Barthélémy D, Dauzat J and Auclair D (1995) A model simulating above- and below-ground tree architecture with agroforestry applications. *Agroforestry Systems* 30: 175-197