



Using plant architectural models for estimation of radiation transfer in a coconut-based agroforestry system

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Key words: *Cocos nucifera*, computer simulation, intercropping, radiation budget, shading, *Theobroma cacao*

Abstract

Software modules have been developed to predict the radiative environment of plant stands consisting of computer ‘mock-ups’ of plants. The architecture of plants used for the computation of radiative characteristics was described at the level of individual organs and simulated according to botanical rules. Three-dimensional stochastic numeric mock-ups were computed for coconut (*Cocos nucifera* L.) and for cacao (*Theobroma cacao* L.) according to the ‘AMAP’ methodology. Then the numerical radiative models were applied to these ‘virtual plants’ to describe the radiative budgets of individual plant parts and entire plants. Modelled light transmission through virtual coconut canopies was in good agreement with field measurements for different treatments and management practices including palm ages, varieties, and planting densities. In a second stage, combining the computer models of coconuts and cacao in a multistrata system, the fraction of radiation that was transmitted through the coconut canopy and intercepted by cacao was successfully simulated.

Introduction

In multistrata agroforestry systems, transmitted photosynthetically active radiation (PAR) is often a limiting factor for the establishment, growth and yield of annual and perennial intercrops. Knowledge of the radiative climate under a given stand, according to age, planting density, and planting pattern, is thus of major interest for the management of coconut (*Cocos nucifera* L.)-based multistrata agroforestry systems.

Many three-dimensional models of light interception and transfer by plants have been developed (Jackson and Palmer, 1979; Mann et al., 1980; Norman and Welles, 1983; Wang and Jarvis, 1990; Stockle, 1992; De Castro and Fletcher, 1998; Röhrig et al., 1999; Sinoquet and Le Roux, 2000). Some are designed for simple discontin-

uous canopies composed of rows of plants with no explicit description of the crowns (Jackson and Palmer, 1979). The models of Kimes and Kirchner (1982) and Sinoquet and Bonhomme (1992), based on the turbid medium analogy, divide the space into three-dimensional cells characterised by their leaf area density and inclination distribution, and thus can potentially be used for any three-dimensional plant structure. Other models are based upon well identified crown forms, such as spheres, ellipsoids or trapezoids, which can be described relatively simply through parametric equations (Norman and Welles, 1983; Goel and Grier, 1988; Wang and Jarvis, 1990; Cescatti, 1997; Röhrig et al., 1999). Alternatively, the Maestro model developed by Wang and Jarvis (1990), and the various models derived from it (Lawson et al., 1995, 1997), combine the descrip-

tion of geometric forms with a three-dimensional subdivision of space into sub-units in which various variables are defined, such as leaf area density or leaf angle distribution functions. Quite complex canopies can be modelled in this way. However, in heterogeneous, plurispecific canopies, these characteristics may vary according to complex horizontal and vertical profiles, which are difficult to describe by parametric equations.

The following numeric radiative model is based on three-dimensional architectural plant models and can be applied to any stand for which a computer-based representation of the architecture exists. Taking into account both the architecture and the dynamics of tree growth, Hallé and Oldeman (1970) identified 'architectural models', based upon general classification criteria. This theory has been further developed by Reffye et al. (1995) at the CIRAD Plant Modelling Unit (AMAP) and formalised using a numeric approach. The architecture of any plant generally consists of successive shoots called 'growth units', often equivalent to 'growth flushes'. A growth unit is produced by a terminal meristem and is usually composed of a series of internodes and nodes that carry leaves. From the botanical observation of growth units and their classification (axis order, physiological age, long/short axis), frequency distributions of numbers of internodes per growth unit can be computed and theoretical distributions fitted (Poisson, binomial, geometric). The occurrence of branching can be fitted to theoretical processes of the Markovian family. A specific protocol was designed which includes measurement of the plants in the field, coding of the data and computation of the laws and parameters of the growth and branching processes (Godin et al., 1999). Three-dimensional plant computer 'mock-ups' are stochastically simulated through the AMAPsim generator according to the growth and branching models fitted to the architectural data (Barczi et al., 1997).

In a former study, Dauzat and Eroy (1997) have described a series of software modules to predict the radiative environment under coconuts and subsequently the yield of the annual crops corn (*Zea mays* L.) and mungbean (*Vigna radiata* L.). The plants used for the computation of radiative characteristics were first described at the level of individual organs and simulated stochastically

according to botanical rules. Numerical radiative models were then applied on these 'virtual plants' to describe the radiative budget of each individual plant within each virtual scenario. The aim of the present paper is to present these modules and their validation process, and to provide an example of their application in multistrata agroforestry systems with cacao (*Theobroma cacao* L.), a perennial understorey crop.

Methods

Development and validation of the modelling approach

In their study, Dauzat and Eroy (1997) computed three-dimensional numerical mock-ups of coconut trees. They placed these numeric models within virtual scenarios, according to the layouts observed in the field. They then calculated average values of transmitted PAR reaching the ground and mapped the spatial distribution under three-dimensional 'virtual' coconut stands in different situations. Finally, they compared these calculations with field measurements in a few characteristic situations in the Philippines. This validation process has been pursued further in the present study by applying it to several varieties in Vanuatu and different planting densities in the Ivory Coast.

Measurements and simulation of plants

Description, modelling and simulation of coconut stands

Field measurements on coconut stands were conducted at three sites representative of commercial coconut-based farming systems: Port-Bouet research Station (Ivory Coast), the Vanuatu Agricultural Research and Training Centre, and the Davao Research Centre of the Philippines Coconut Authority. Coconut age, variety, planting pattern and density varied among these stands (Table 1). Architectural observations were taken on a stratified sample of 50 coconut trees representative of each site. Further detailed descriptions and measurements were taken on 20 trees under which radiation transmission was measured.

Coconut follows the architectural model of Corner (Hallé and Oldeman, 1970). It is charac-

Table 1. Plant material and planting design for experiments with *Cocos nucifera*.

	Variety	Age (years)	Planting density (stems ha ⁻¹)	Planting pattern ^a
Côte d'Ivoire	WAT × RLT ^b	16	115	Triangular
		16	143	Triangular
		16	180	Triangular
Philippines	Laguna Tall	5	143	Triangular
		20	143	Triangular
		40	156	Square
Vanuatu	Vanuatu Tall	6	143	Triangular
	VRD × VTT ^c	10	143	Triangular

^a rows all oriented North-South.

^b WAT × RLT = West African Tall × Rennell Tall.

^c VRD × VTT = Vanuatu Red Dwarf × Vanuatu Tall.

terised by 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: i) total trunk height, trunk diameter at one metre height, trunk inclination and azimuth, and the number of green fronds of all sample trees; ii) frond characteristics of 50 to 100 fronds from five representative trees (i.e., petiole and rachis length, leaflet number and location, inclination at the junction of the petiole and rachis, rachis curvature); and iii) detailed leaflet characteristics (i.e., total length and width every 10 cm and insertion angles of the leaflets), which were assessed for a subsample of 20 fronds. Data for each site and species were fitted using polynomial, exponential or trigonometric functions for each parameter. The fitted parameters with their standard deviations were then synthesised into a data file used to generate stochastic three-dimensional numeric mock-ups in accordance with the observed intra- and inter-tree variability.

Description, modelling and simulation of cacao

Architectural measurements of cacao were taken in mixtures of hybrids in Gunung Batin, central Lampung (Indonesia), either in monocultures or in coconut intercrops. Cacao development follows the architectural model of Nozeran (Hallé and Oldeman, 1970). The main stem has a sympodial development, composed of a succession of rhythmically growing modules, each one ending

in a tier of plagiotropic lateral branches. The complete descriptions of 150 young cacao trees included the number of growth flushes and internodes, identification and description of the three types of axis (orthotropic trunks, plagiotropic branches and twigs), and their location. Total trunk height and trunk diameter at 20 cm height were recorded. The growth and branching processes were analysed for each type of axis (the number of flushes, number of internodes and their length were noted), and the branching analysis provided the number and distribution of branches and twigs (Mialet-Serra, 1998). Using the stochastic plant generator software 'AMAPsim' (Barczi et al., 1997), three-dimensional numeric plant mock-ups were generated from the plant data files and the parameters of discrete binomial and exponential fitting laws which describe growth processes, and conditional (Markovian) probabilities for branching processes. Virtual stands of coconut intercropped with cacao were then computed and radiative climate was simulated using the MIR, MUSC, and AMAP_lux modules described below.

Radiation 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 in two adjacent triangles delimited by four neighbouring coconuts (triangular planting pattern; Table 1). Each triangle was divided into 16 sub-triangles with a sensor placed

in the centre of each. On the numeric plant mock-ups, three specific modules (MIR, MUSC, AMAP_lux) were used to simulate radiative transfers within the stand:

- MIR calculates the incident radiation intercepted by elements of vegetation (organs). This model uses the Z-Buffer technique to generate images of the scenario observed from 46 directions resulting from a regular division of the sky hemisphere. Each element of the canopy (e.g., a leaf) observed on an image receives part of the incoming radiation from the direction that corresponds to that image, proportional to its number of pixels on the image. Each image also gives the distribution of light received by the soil from that direction.
- MUSC calculates the multiple scattering of light within the canopy, which can be divided into any number of horizontal layers (ideally around 10), including the soil surface. It is based on mutual irradiation coefficients between pairs of canopy layers. These coefficients, as well as the interception of incident light by layers, are outputs of the MIR module. MUSC proceeds by iterations to calculate light exchange between layers for all the 46 defined directions (upward and downward).
- AMAP_lux combines the previous results according to radiative conditions, which are

provided by a meteorological data file. It first calculates the quantity of light arriving at the scenario from the 46 defined directions. In a second step, it calculates the first order irradiation (resulting from incident light interception) for each canopy element and then the budget for multiple scattering for each canopy layer. Lastly, it calculates the total irradiation of each canopy element, assuming that the canopy elements within a layer intercept scattered radiation proportionally to their area. AMAP_lux also combines the 46 images output by MIR to generate a map of radiation reaching the soil. All AMAP_lux outputs are integrated over the time period specified in the meteorological data file.

Results

Estimated vs. measured radiation transmitted by a coconut stand

The daily evolution of PAR transmission under coconut stands was satisfactorily simulated (Figure 1). Dauzat and Eroy (1997) had observed, for a given planting density, important variations of PAR transmission with age due to increasing crown sizes from five to 15 years and a gradual

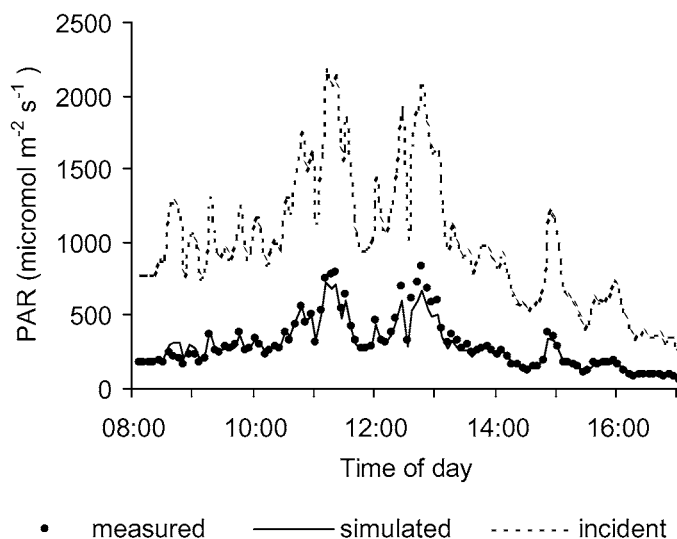


Figure 1. Example of daily evolution of photosynthetically active radiation (PAR) transmitted under 10-year-old VRD \times VTT *Cocos nucifera* at 143 stems ha⁻¹ in Vanuatu in relation to incident radiation.

decrease after age 20 (Figure 2, right, reproduced from Dauzat and Eroy, 1997). The trends observed in the present studies of other experimental designs confirmed that simulations were in good agreement with average field measurements (Figure 2, left and centre): for a given age, PAR transmission was linearly related to coconut density, irrespective of planting pattern, and PAR transmission was higher under the Vanuatu Tall variety than under the hybrid.

Maps of the spatial distribution of light reaching the ground (Figure 3) were produced for a coconut-based system, providing information on the distribution of light and its intensity. The average daily radiation varied between 100 and 200 micromols $\text{m}^{-2} \text{s}^{-1}$ with less light near the coconut trunks.

Estimated radiation intercepted by a cacao understorey

Virtual scenes were computed for a coconut-cacao intercropping system (Figure 4). The radiative budget was then calculated for each component, producing estimates of the intensity of light available within the cacao stratum. The simulated daily evolution of PAR intercepted by a fully grown cacao crop under coconuts was different for clear (diffuse/global = 0.23) or overcast sky (diffuse/global = 1) (Figure 5). Nevertheless, when integrated on a daily basis, the total transmitted radiation intercepted by cacao was constant, irrespective of external conditions.

Discussion and conclusions

Good agreement was obtained between the estimated PAR through a coconut canopy and field measurements at several sites for several varieties with various planting patterns and densities. By using three-dimensional numerical mock-ups of coconut linked to the radiation calculation modules, the distribution of transmitted radiation reaching the soil under a coconut stand could be estimated accurately for various planting patterns. Dauzat and Eroy (1997) used this method to predict the yield of understorey corn and mungbean intercrops as a function of estimated transmitted PAR in several planting patterns and densities of coconut trees. They assumed that the radiation reaching the soil represented the radiative environment under the coconut canopy that was available for the annual crop. In the case of a multistrata system with a much larger perennial understorey crop such as cacao, the calculation of the radiative budget must be performed on scenarios which include computer models of both components of the association. It is then possible to simulate that fraction of radiation transmitted through the coconut canopy which is actually intercepted by the perennial understorey crop. However, in the case of intercropping of coconut and cacao, light is probably not the main growth-limiting factor. Early results have shown that some architectural features of young cacao can be influenced by the amount of shading, leading to differences between monoculture and intercropped

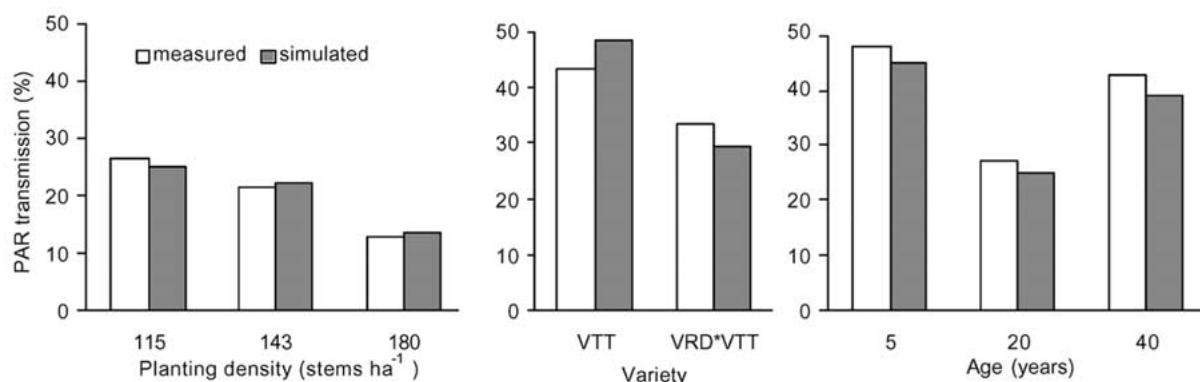


Figure 2. Comparison of measured and simulated average photosynthetically active radiation (PAR) transmission under *Cocos nucifera*, integrated over three days, according to planting density in Côte d'Ivoire (left), to variety in Vanuatu (centre), and to age in the Philippines (right; reproduced from Dauzat and Eroy, 1997).

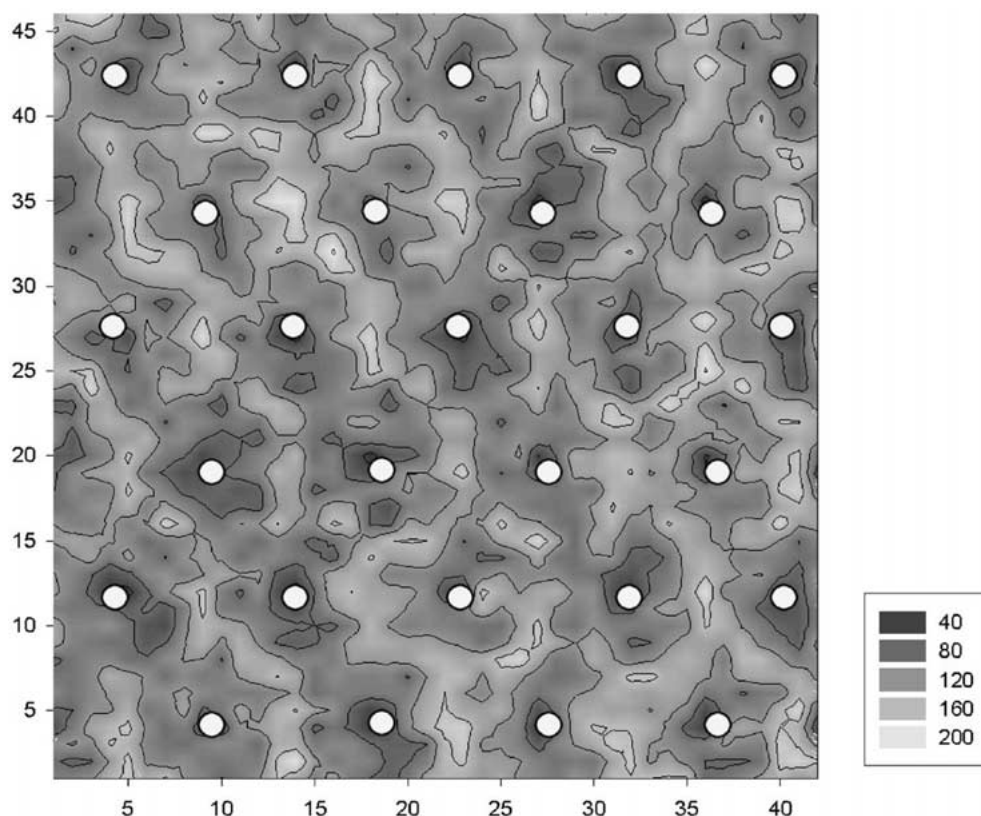


Figure 3. Spatial distribution of transmitted light under 10-year-old VRD \times VTT *Cocos nucifera* at 143 stems ha^{-1} in Vanuatu. The units on the horizontal and vertical axis are local coordinates (in metres). Shades of grey correspond to average daily radiation received by the soil (in $\text{mol m}^{-2} \text{s}^{-1}$). Circles represent tree positions.

conditions (Mialet-Serra, 1998). The architectural development of a cacao tree, particularly the position of flowers and the development of fruit, is probably as important for yield predictions as photosynthetic rate. For a better understanding of cacao production, it will probably be necessary to simulate the carbon balance locally within the crown of trees.

The main advantage of this model is that it can be applied to any plant, and to various management designs, such as planting pattern, spacing, or pruning. It is possible to assess the radiative budget not only of the whole canopy or different strata but also of each individual plant and, if necessary, provide details at the level of each plant organ. It is also possible to control each architectural parameter (phyllotaxy, leaf or leaflet geometry, orientation, etc.). The radiation budget modules can be applied to any numeric plant

mock-up, including plants with more complex architecture than coconuts.

In addition to the possibility to perform 'virtual' experiments in which age, planting density, planting pattern and pruning intensity can vary, and therefore of adapting management practices according to the PAR requirement of the intercrop, the combination of numeric radiative models with three-dimensional plant models opens wide perspectives for the simulation of plant ecophysiological response (Reffye et al., 1999). For example, the hydraulic structure of digitised coffee plants has been modelled and their transpiration simulated according to radiative conditions (Dauzat and Rapidel, 1998; Dauzat et al., 2001). After validation, the model was used to assess the effect of *Erythrina* sp. shade on coffee transpiration (Rapidel et al., 1999). Such integrated modelling is being pursued further to simulate



Figure 4. Computer-generated image of a multistrata stand consisting of 24-month-old *Theobroma cacao* intercrops under 6-year-old *Cocos nucifera*.

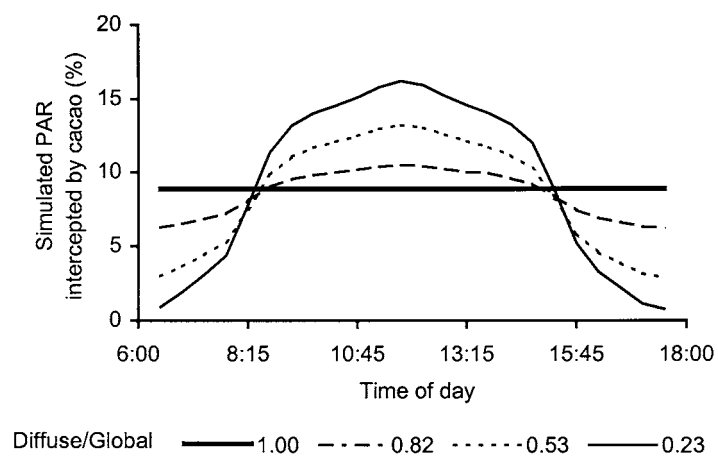


Figure 5. Example of daily evolution of photosynthetically active radiation (PAR) intercepted by a fully grown *Theobroma cacao* stand in Vanuatu, simulated for different external radiative conditions (ratio of diffuse to global radiation).

transpiration and photosynthesis of coffee and cacao in multistrata agroforestry systems.

Most process-based models require a relatively large amount of field measurements to estimate the parameters of the different functions and many field experiments may be necessary. The present method can produce a large number of different 'virtual scenarios' with computer mock-ups from which the parameters necessary for process-based models can be estimated. Once the architectural parameters have been determined, a great amount of fieldwork can be saved by testing many different management options with 'virtual' experiments (Reffye et al., 1999). Simple parameters, such as leaf area index or extinction coefficients, can be computed according to plant architecture as can other parameters which are not readily measured directly in the field. Such an application is currently under investigation in two different European collaborative projects with the Maestro (Lawson et al., 1997) and WaNuLCAS (van Noordwijk and Lusiana, 1999) models.

However, the method described here has two main limitations. The first is the large amount of field work necessary to understand and measure the architectural development of more complex species. However, sensitivity analyses can be performed in order to minimise or avoid the collection of architectural parameters whose effect on light interception is minor or negligible. Furthermore, preliminary (unpublished) results have shown that measurement protocols can be reduced for the description of certain parameters. For example, all the leaflets on one side of a coconut frond can be represented by a single continuous lamina, for which a specific transmittance value can be computed to account for the inter-leaflet spaces. The second limitation is the computation time required. If each leaflet is represented by six polygons, then each coconut tree is composed of approximately 50,000 polygons and a virtual scenario of 52 coconut trees requires 2.6 million polygons. Ten hours of computation time was required to calculate the radiative budget for such a scenario for 46 directions. Here again, the above-mentioned sensitivity analysis can reduce the number of parameters involved, and hence the computation time. Alternatively, for less precise calculations, simplified tree mock-ups can be used.

There is an increasing interest in functional-structural tree models to analyze tree growth and development (Le Roux and Sinoquet, 2000). Despite the above-mentioned limitations, the combination of morphological models with process-based models appears very promising in complex heterogeneous situations such as multistrata agroforestry systems (Sievänen et al., 2000).

Acknowledgements

This research was partly funded by the European Commission, STD3 programme, contract TS3 CT 92-0132.

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