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Simulating light regime and intercrop yields in coconut based farming systems

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Abstract

Intercropping experiments of corn and mungbean have been conducted at the Davao Research Center of the Philippines Coconut Authority under coconut stands at different densities. Yields obtained in these experiments are more or less linear functions of the photosynthetically active radiation measured under the trees. In order to extrapolate these results for other palm ages and densities, the following steps have been achieved: (1) measurement and modeling of the architecture of 5, 20 and 40 year old palms, (2) generation of virtual coconut stands, (3) simulation of light transmission using these virtual stands, (4) prediction of intercrop yields by combining the results of intercropping experiments and the simulated light transmission. The simulated light transmission under 5, 20 and 40 year old coconut stands were close enough to field measurements to consider that both computerized coconut mock-ups and radiative models are valid. Radiative simulation experiments could thus be performed in order to assess the effect of coconut density on photosynthetically active radiation (PAR) transmission as well as the effect of frond pruning. Results exhibit a nearly linear relationship between light transmission and tree density. Pruning also appears as an effective mean of increasing the light permeability of coconut stands. These results are interpreted in terms of corn and mungbean yields by combining radiative simulations and field intercropping experiments. © 1997 Elsevier Science B.V.

Keywords: Plant architecture; Radiative transfers modeling; Coconut; Intercropping; Cocos nuciferal

1. Introduction

An accurate modeling of the photosynthetically active radiation (PAR) regime is essential to predict the behavior of intercrops in agroforestry systems such as coconut based farming systems (CBFS) where PAR received by intercrops is commonly 1/4 to 1/3 of the PAR in open field. Intercropping experiments under coconuts in the Philippines demonstrated that, in the absence of strong water deficit and with a proper fertilization supply, the intercrop yields are more or less linearly related to the available PAR (Bénard et al., 1996). Thus optimizing CBFS can be achieved mainly through the choice of coconut density or by frond pruning in order to get sufficient light for intercropping.

Few coconut density trials exist because they are lengthy and expensive. Moreover, the density is not the only factor to be taken into account: the development of palms, their planting pattern and the radiative

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conditions affect the intercrops potentialities. A radiative model accounting for all these factors is thus essential for understanding and optimizing CBFS.

Classical radiative modeling represents plants as simple shapes (e.g. spheres, cones, cylinders…) without taking into account the actual plant geometry inside these shapes (Brown and Pandolfo, 1969; Chiapale, 1975; Charles-Edwards and Thorpe, 1976; Li and Strahler, 1985; Riou et al., 1989) or uses global statistical canopy properties but disregard spatial arrangement between plant items (Kimes, 1984; Sinoquet, 1989). Recent 'architectural' models such as the coconut models used in this study offer a much more realistic representation of plants because they are based on their botanical description, taking into account the precise shape of plant organs as well as their spatial or geometrical organization in three-dimensional space (Reffye et al., 1988; Goel et al., 1991; Aries et al., 1993; Dauzat, 1995). The recent development of software generating realistic three-dimensional models of plants opens new possibilities for the radiative transfer modeling. This elicited the interest of the Plant Modeling Unit of CIRAD to develop a specific radiative software exploiting the three-dimensional information attached to the computerized plant mock-ups.

Initial studies on oil palm and coconut in Ivory Coast (Girard, 1992; Dauzat, 1994) showed that radiative climate can be assessed acutely on these computer models and plant architecture variations having significant bearing on transmission can be identified. Moreover, climatic factors, especially the quantity and variation on sky condition, can be assessed. This enables prediction as to radiative climate in a given stand considering its density, age, planting pattern and seasonal fluctuations of radiation. The horizontal distribution of light at the soil level is also assessed as illustrated in Fig. 5.

2. Material and methods

2.1. Experimental site and plant material

2.1.1. The site

Field experiments have been conducted at the Davao Research Center (DRC; 07° 05 N, 125° 57′ E) of the Philippines Coconut Authority (PCA). The climate is characterized by average annual rainfall of 2400 mm/year fairly well distributed throughout the year, a relative humidity of 73–82%, a mean temperature of 27°C and annual sunshine duration of 2350 h. The gently sloping soils are well drained and their average composition is 28% sand, 31% silt and 41% clay. The pH (H_2O) is 6.6.

2.1.2. The coconut stands

Tree description and radiative measurements have been done within three stands of LAGUNA TALL coconuts. The first stand is composed of 5 year old trees planted in a 9 × 9m triangular pattern with rows oriented North-South. The second is composed of 20

Table 1

Corn and mungbean varieties used in intercropping campaigns at the PCA Davao Research Center

Crop	Intercropping campaigns			
	1st	2nd	3rd	4th
Corn	USM var. 6	USM var. 6	USM var. 6	USM var.6
	USM var. 2	USM var. 2	USM var. 5	USM var. 2
	SMC 357	USM var. 10	USM var. 8	USM var. 5
		SMC 357	IPB H921	P3246
		IPB H921	P3246	CPX 3007
		P3246	XOF 62	P3022
Mungbean	Pag-asa 7	Pag-asa 7	Pag-asa 7	Pag-asa 3
	Pag-asa 3	Pag-asa 3	Pag-asa 3	BPI Mg 7
	BPI Mg 7	BPI Mg 9	BPI Mg 9	BPI glabrous 3
	BPI Mg 9	Candelaria	Candelaria	BPI Mg 9
	BPI Mg 60	Local, Davao	Local, Davao	PAEC 5
	BPI glabrous 3	Sariaya	Sariaya	Local, Bansalan

year old trees planted with the same pattern as above. The third stand was planted 40 years ago in square design, with a 8 × 8m spacing.

Rational felling of certain palms within the 20 year old stand 1 m above the ground created a density and lighting gradient which determined the intercropping treatments (Fig. 7):

- (L1) standard interrow (control)
- (L2) standard interrow with greater lateral lighting
- (L3) thinned interrow
- (L4) very thinned interrow

2.1.3. The intercrops

Four intercropping campaigns have been practiced for corn and for mungbean (*Mungo radiata*) within the thinned 20 year coconut stand between 1991 and 1994. The land was tilled prior to sowing with a disc plough and ridged. The crops were planted in North-South strips down the middle of the coconut interrows, leaving a free corridor either side of the palm rows. They received the fertilizers and phytosanitary treatments usually practiced in the region. Different combinations of varieties were tested for each campaign as indicated in Table 1. More details about these intercropping trials are given in Bénard et al. (1996).

2.2. Description of coconut stands

The stand description included the description of the individual trunks (diameter, height, projection and azimuth; see Fig. 1) as well as of the number of green fronds per tree. In order to assess the inter-trees variability, 50 palms were sampled within the neighborhood of the plots used for radiative measurements for each age group.

Ten palms were sampled to get the phyllotaxic angle from leaf scars along the trunk. The value was controlled later on other trees by angle measurement between fronds of rank 9 and 14.

The frond length (petiole and rachis) was measured

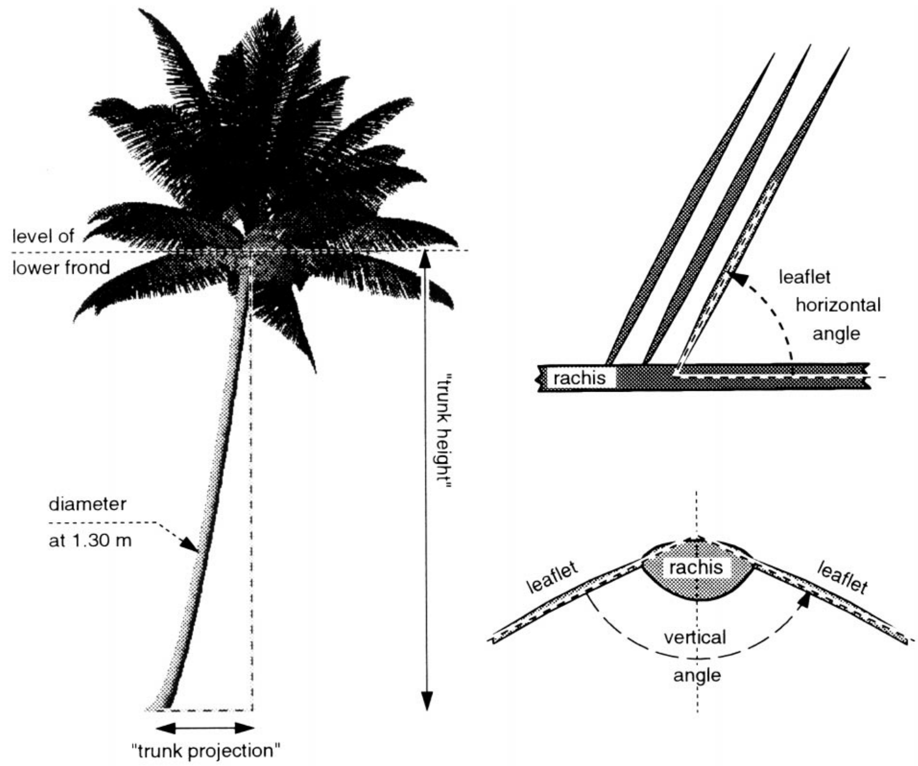


Fig. 1. Definition of some coconut architectural parameters.

on 100 dry fronds from different trees for each age group. In addition, to study intra-tree variability, all the dry fronds produced during a year have been measured on five trees per group.

The frond inclination at the junction of petiole and rachis was measured on the most number of leaves on five trees per age group using an electronical clinometer. In order to model frond curvature, the height of some points along the rachis was measured. All accessible fronds (i.e. fronds of rank above 6 or 7) of 10 young palms (under 10 years old) were sampled.

The leaflet number was counted on both sides of three fronds taken from the five trees selected per age group. This counting was done on 50 cm long sections of rachis in order to assess the spacing of the leaflets. Three unbroken leaflets were taken on each side of the 50 cm sections in order to measure their length, width and surface area. These measurements were obtained by an opto-electronical planimeter (LICOR leaf area meter) after masking the gaps within the lamina if ever.

The vertical and horizontal angles of leaflet insertion (see Fig. 1) were measured on photos of 10 cm long segments of rachis. All the fronds of an apparent phyllotaxic spire were taken from two trees of each age group. Segments were then cut approximately every 40 cm for photos.

2.3. Modeling of coconut architecture

The morphogenetic growth pattern of coconut adheres to Corner's architectural model (Hallé et al., 1978), which is characterized by the existence of a single leaf axis with lateral inflorescence like in oil palm and papaya. Thus the description of the plant topology is quite simple, but an accurate geometrical description is needed for our purpose.

Some palm features were conveniently characterized by a mean and a SD, assuming a Gaussian distribution (Dauzat and Eroy, 1995). It is the case for the parameters of the trunk (height, diameter, projection, azimuth), the frond number and their phyllotaxy, the number of leaflets on each side of the fronds.

Other features have been fitted with simple functions (Dauzat and Eroy, 1995). For instance, a power function was used to fit the frond inclination at petiole end against the frond rank, a quadratic function to fit the leaflet spacing against their rank and a sinusoidal function to fit the leaflet length against their position on the rachis. The leaflet area has been fitted with a power function of their position on the rachis.

The frond curvature is modeled as a flexing beam subjected to gravity by a sub-program. The two parameters of this sub-program (the *Young modulus* and

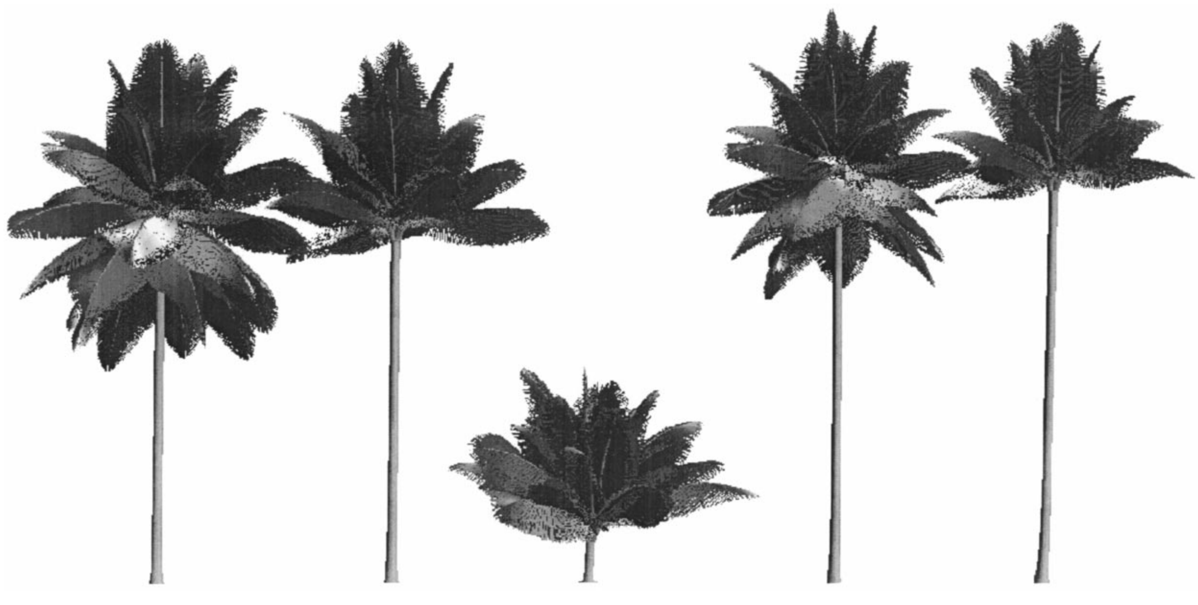


Fig. 2. Simulated mock-ups of 20 (unpruned/pruned), 5 (unpruned) and 40 year old (unpruned/pruned) coconut trees.

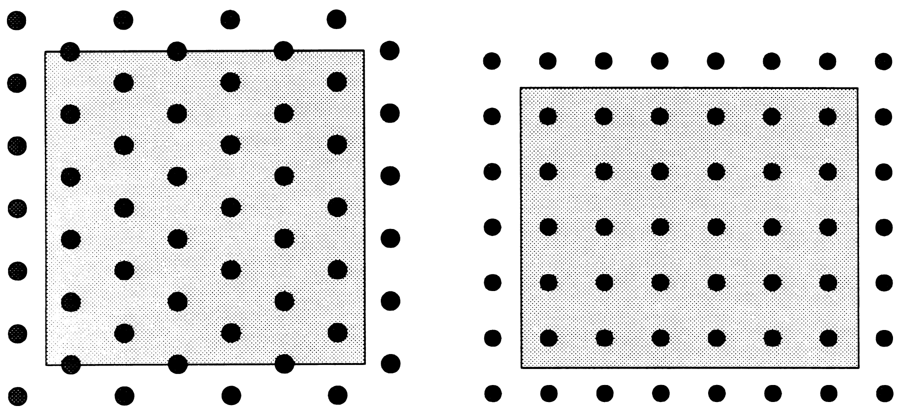


Fig. 3. Simulated scenes with triangular design (left) and square design (right). Circles indicate coconut positions and inner rectangle represent the effective area used for radiative simulations (assuming that the stand portion within this area is surrounded by identical stand portions all around). The triangular design was used with a distance between trees of 8.5, 9, 10 and 11 m and the square design was used with a distance between trees of 8, 8.5, 9 and 10 m.

the *conicity*) have been fitted using a specific interactive program.

2.4. Simulation of virtual coconut stands

The coconut generator program is a software which computes the tree geometry through the functions chosen for modeling. The palm generation is stochastic, i.e. restitutes the observed tree variability (Reffye et al., 1995). Thus the input parameters are specified with their variability. Some parameters pertain to the global features of the observed population with the inter-tree variability: phyllotaxic angle, height and diameter of trunk, number of fronds. Other parameters, like the frond length or the number of leaflets, are given with the intra-tree variability.

One parameter file was created for each age group. In order to test the effect of pruning on transmitted radiation we also simulated pruned trees using the same parameter files but limiting the number of fronds to 18 (Fig. 2).

To analyze the effect of the planting patterns and of the tree density, we created scenes with square and triangular designs, at different spacing (Fig. 3). Scenes in square design had 56 trees with eight rows of seven coconuts. Four densities were used, 100, 123, 138 and 156/ha, corresponding to distances between trees of 10, 9, 8.5 and 8, respectively. Four

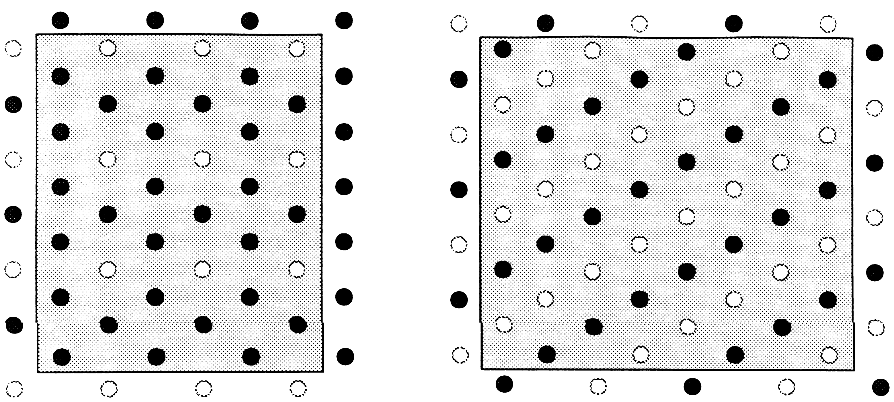


Fig. 4. Simulated thinned stands. Same as legend in Fig. 4 with felled trees represented by empty circles. Thinning original stands at 143 trees/ha leads to densities of 107 (left) and 72 trees/ha (right).

Fig. 5. Simulation of the light transmitted under a 20 year old coconut stand at density 143 during a day.

rows of seven coconuts and four rows of six coconuts were included in scenes with triangular planting. Four densities were used: 81, 115, 143 and 160 trees/ha, corresponding to planting distances of 11, 10, 9 and 8.5 m, respectively.

Three other designs were simulated by removing some palms from the triangular design at density 143. The first one represents the DRC experiment (Fig. 7). The other two result from a thinning down to 107 and 72 palms/ha (Fig. 4).

The same computerized trees are used for simulating stands at a given age, assuming that the coconut density and planting design do not deeply affect the tree development. Data previously collected in a coconut density experiment in Côte d'Ivoire with densities ranging from 115 to 180 trees/ha showed that this statement is acceptable (Girard, 1992).

2.5. Radiative measurements

In characterizing the radiative conditions in CBFS, the main concern is to assess the quantity of transmitted PAR, the part of the solar spectrum used by the chloroplasts for photosynthetic conversion. The transmitted PAR under the 5, 20 and 40 year old coconut stands was measured by a set of quantum sensors at the soil level in the absence of intercrops while the incident radiation was recorded by a reference sensor placed above the canopy or in open ground.

The sensors used for measuring the transmitted radiation were manufactured by the CIRAD because of their low cost as compared to the commercial sensors. They were made with amorphous silicon cells, so-called SLAMs, which have a spectral sensitivity within the 400–700 nm waveband, though a very slight overlapping with adjacent wavebands (UV and NIR) occurs. The cells were equipped with a precision resistor. The whole was sprayed with a waterproof varnish and inserted in a black case made within a nylon bar. A white cover acting as a diffuser was placed above the cell. A commercial sensor was used as a reference for the calibration of these sensors.

To determine not only the mean transmission rates but also to map the distribution of light, the protocol called for the use of 32 SLAM sensors placed in two adjacent elementary triangles[1]. The sensors were connected to a Delta-T logger programmed to read the signals every 5 s and to integrate them every 5 min. Each of the three stands had at least 3 days of continuous logging from approximately 0600 until 1700 h.

2.6. Simulation of radiative climate under coconut stands

The software developed split the sky hemisphere in 46 sectors according to the Den Dulk's 'TURTLE' model (Den Dulk, 1989). The quantity of PAR incoming from each direction is calculated in two steps:

- First direct and diffuse components of global radiation are calculated from the ratio of global radiation on extra-terrestrial radiation using de Jong formulas (cited by Spitters et al., 1986).
- The distribution of diffuse radiation within the 46 sectors is then calculated by combining the formulas of Dogniaux (1973) describing the brightness of a clear sky and of Anderson (1966) describing the brightness of a standard overcast sky. Instantaneous direct radiation is distributed into three neighboring sectors according to the spherical distance of their center to the sun direction.

The sector brightness can be calculated for a given moment or integrated on several hours or several days with a 30 mn time step.

Radiative transfers within the canopy are simulated by two programs developed at the CIRAD Plant Modeling Unit (to be published): for each of the 46 sectors defined:

- The MIR program calculates the interception of the incident radiation by the vegetation elements and by the soil. Light interception can be output for each canopy element (e.g. each leaflet), for element classes (e.g. for fronds according to their rank) or for individual plant. A map of the radiation reaching the soil can be obtained (Fig. 5).
- The MUSC program calculates the multiple scattering of the intercepted light at different levels of the canopy, i.e. the mutual lighting between the soil and horizontal layers of vegetation. Resulting light interception is output for each layer defined by the user and for the soil.

These two complementary programs provide a detailed radiative balance of the canopy illuminated from each direction. The RADBAL module then combines the results obtained for the different directions according to the instantaneous or integrated sector brightness. Owing to this procedure, the directional radiative exchanges have to be calculated only once and the total radiative balance can then be obtained rapidly for any radiative condition (Rapidel, 1995).

3. Results

3.1. Radiative simulations

3.1.1. In situ measurement and validation of radiative simulations

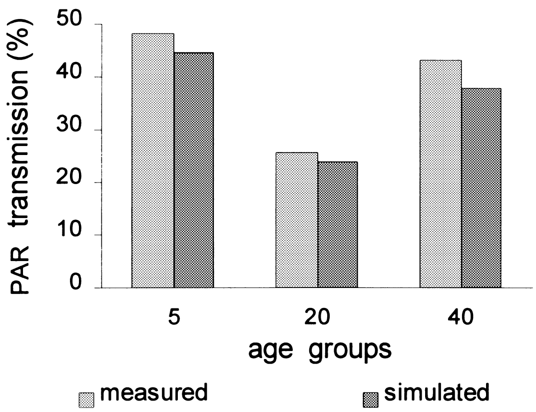
The measured rate of light transmission substantially varies with age (Fig. 6). This results from a crown development (frond length, declination and number of fronds) increasing from early stages to reach its maximum on the 15th year and decreasing gradually beyond 30 years.

Simulations have been run for coconut stands with bare soil, i.e. without intercrop. In the absence of data about soil and coconut leaf optical properties in the PAR domain, plausible values have been tested:

- 10, 20 and 25% for the leaf reflection and transmission coefficients (assumed to be equal)
- 5, 10 and 15% for the soil reflection coefficient.

Simulations showed that PAR at soil level depends very slightly on the chosen optical properties (Dauzat and Eroy, 1995); actually, the light fraction impinging on the soil without interception by the vegetation is much more important than the fraction scattered by

[1] An elementary triangle is the space delimited by three neighboring trees.



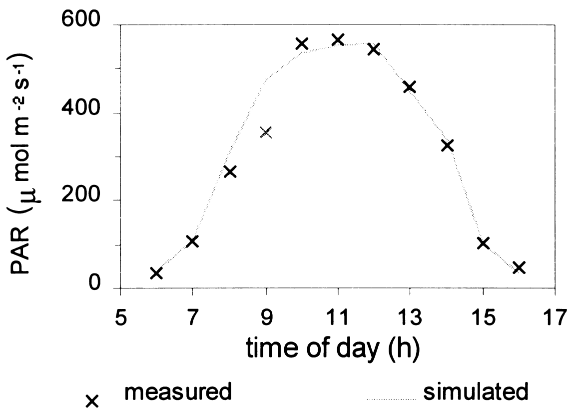


Fig. 6. Upper, Comparison of simulated and measured PAR transmission under coconuts for different age groups. Lower, Daily evolution of the PAR transmitted under a 20 year old coconut stand.

the vegetation toward the soil. Thus we chose arbitrarily a reflection-transmission coefficient of 20% for the leaves and a reflection coefficient of 10% for the soil. One could expect that the presence of an intercrop with an albedo higher than the albedo of the soil would modify the radiative balance of the canopy. In practice this modification is negligible: the presence of an intercrop with an albedo of 20% would barely increase the downward PAR radiation under coconuts by about 1%.

The PAR transmission has been simulated for 5, 20 and 40 year old observed stands on the whole period of in situ radiative measurements. The average simulated PAR transmission is in good agreement with field data (Fig. 6, left). The diurnal evolution of PAR transmission is also correctly simulated (Fig. 6, right). Likewise, the radiative model was able to simulate the transmitted light in the complex situation of the DRC experiment (Fig. 7). The simulated values for the different treatments are quite close to the measured ones. All these results are satisfactory enough to consider that both the coconut models and the radiative models are valid and can be used for radiative simulation experiments.

3.1.2. Radiative simulation experiments

PAR transmission under 20 and 40 year old coconut stands has been simulated on wide range of tree density and with different planting patterns as presented in Section 2.4. For a given age, the PAR transmission is linearly related to coconut density, irrespective of the planting design (Fig. 8). The regressions of %PAR transmission vs. density give:

$$\%\text{PAR} = 79.97 - 0.386 \text{ density } (R^2 = 0.996)$$

… for 20 year old stands

$$\%\text{PAR} = 85.79 - 0.312 \text{ density } (R^2 = 0.984)$$

… for 40 year old stands

It appears that removing some fronds of the trees (to limit their number at 18) can increase the light penetration by about 25–40%. As a result, the quantities of PAR transmitted under 20 year old pruned stands with densities of 143 and 156 palms/ha are more or less comparable to those obtained under unpruned palms having densities of 95 and 100 palms/ha. Enhancement of light transmission is less marked for 40 year old than for 20 year old coconuts.

3.2. Corn and mungbean yield predictions

The corn and mungbean yields largely differed from one intercropping campaign to another (Fig. 9). This can be mainly attributed to the varieties grown and, to a lesser extent, to temporary water logging (Bénard et al., 1996). Besides these differences, it can be noticed that the yield response for both crops is more or less a linear function of the PAR received.

In order to simulate the expected yields of corn and mungbean grown under coconuts at different densities, we simulated first the PAR available under coconuts. The yields were then obtained by interpolation using the experimental yield responses.

For corn under 20 year old unpruned coconuts, decreasing the tree density to 50%, may mean doubling or tripling the yield (Fig. 10). The yield response of mungbean to the density is proportionally smaller and varies among the campaigns due to the shade tolerance of the varieties (Fig. 11). The pruning of the palms has a drastic effect on the corn and mungbean yield. Globally, the density and pruning effects are smaller for 40 year old stands than for 20 year old stands; because the light permeability is higher for younger trees, the competition for light is less intensive than for older ones.

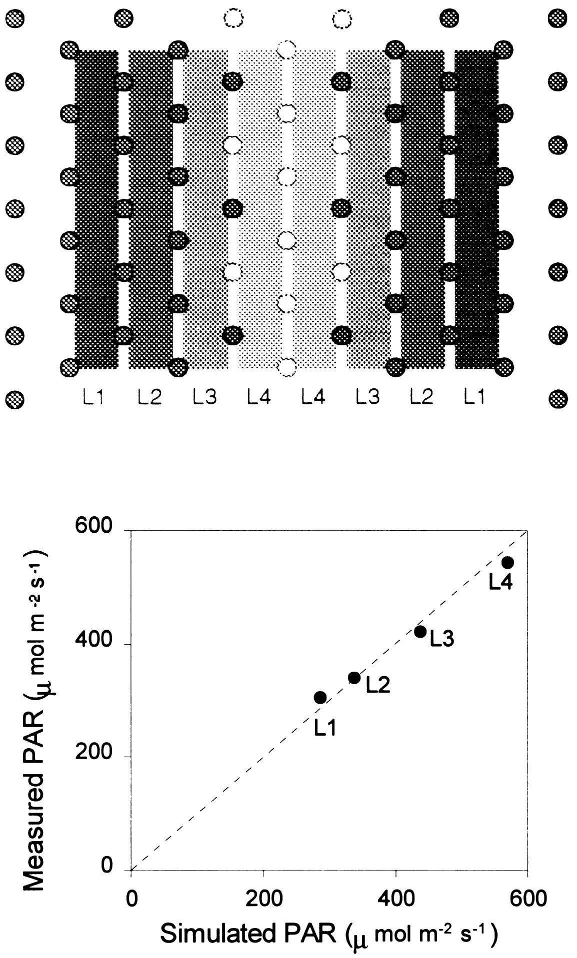


Fig. 7. Upper, Layout of the DRC intercropping layout. Felled palms are represented by empty circles and remaining palms by filled circles. Grey strips indicate the areas used for intercropping experiments. Treatments L1–L4 correspond to lighting gradients resulting from local stand thinning. Lower, Simulated and measured PAR values obtained for the different treatments (average daily PAR).

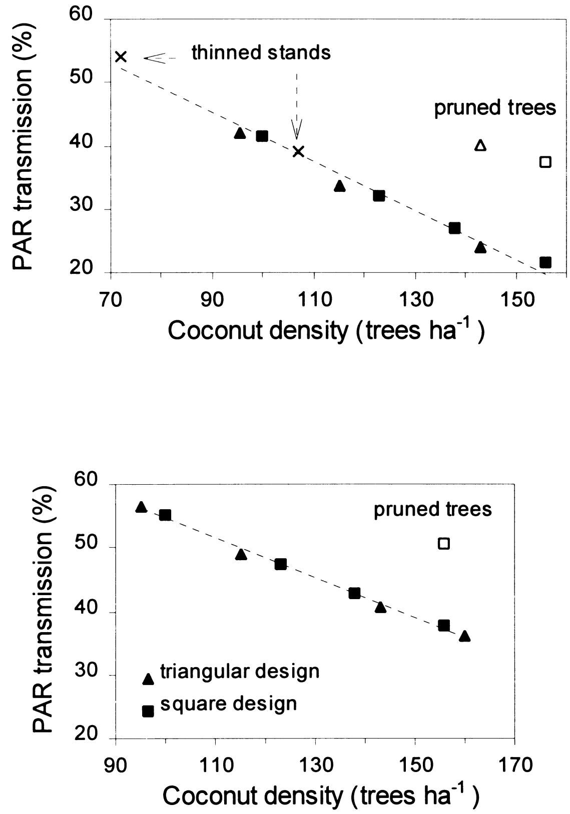


Fig. 8. Simulated PAR transmission vs. density under 20 (upper) and 40 year old (lower) coconut stands.

4. Discussion and conclusions

An original approach involving a coconut generator and specific radiative models was used to predict the radiative climate under coconut stands at different ages and densities. A good agreement was obtained between the simulated PAR and the in situ measurements and the small discrepancies may result from the variability existing under the stand. We can thus consider that both the simulated coconut mock-ups and the radiative models MIR and MUSC are valid.

Actually, the work required to achieve such a study was heavy as compared to the work required by clas-

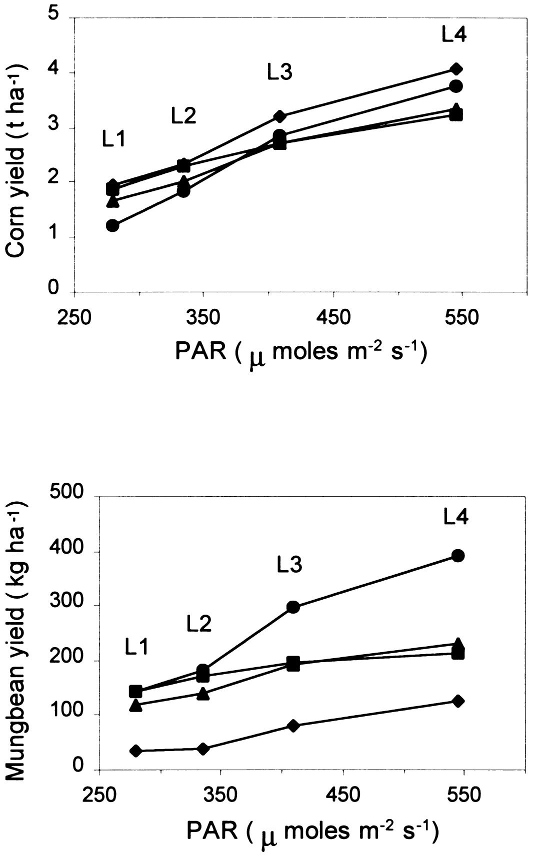


Fig. 9. Experimental response curves of corn and mungbean yield against the average daily PAR value (see Fig. 7 for the explanation of treatments L1–L4). Symbols represent the four intercropping campaigns of corn and mungbean.

sical approaches which rely on a much more simple description of the vegetation; the knowledge of the leaf area index, for instance, can be sufficient to run the Monsi and Saeki's model. In return these simple models have a restricted field of application. Despite such models can be calibrated[2] in order to simulate the actual light transmission rate under a given stand, the extrapolation for other stands, e.g. with other densities, would be risky. The van Kraalingen's model, representing the crown of oil palm trees as a set of panels radially disposed within an hemisphere at the top of the trunk (van Kraalingen et al., 1989), is much more realistic. Nevertheless the validity of this model for different crown geometry (sometimes more spherical than hemispherical) is to be checked and its adaptation to coconut would, at least, need calibration. When using detailed mock-ups, no calibration is needed and the effect of any change in crown geometry can readily be assessed. Furthermore the radiative models MIR and MUSC are independent of the stand constitution; any planting pattern and density can be tested and the inter-trees variability is taken into account. Therefore the use of computerized coconut mock-ups ensures that the radiative simulations will remain valid for any density as long as the tree architecture is not deeply modified[3]. This is quite important in so far as the radiative simulations will lead to recommendations for planting densities and agronomic practices.

Measurements and simulations exhibited large differences between PAR transmission under coconut stands according to their age. Thus, practically, the management of intercropping must account the dynamic of growth of the coconuts and the search for long term optimal solutions must integrate the whole duration of the coconut stand life.

One major result obtained by simulations is that the PAR transmission under coconuts at a given age is sensibly a linear function of the tree density, irrespective of their planting pattern. It is thus possible to adjust the tree density according to PAR requirement of intercrops. Because the light transmission is similar in triangular and square designs, the choice of a coconut planting design may be guided by practical considerations, e.g. ease in cultural practices like cross plowing in square designs. Further simulations are currently done to analyze the distribution of the transmitted PAR, i.e. the PAR quantity actually available for intercrops.

A possible alternative to choosing a lower density for intercropping purposes can be the pruning of the coconuts. The simulations show that limiting the frond numbers to 18 in coconut stands at regular densities is quite effective to enhance the light transmission. Pruning seems a very flexible and cost-effective means to modify the light competition in a coconut based farming system. It can be used in existing stands to obtain the desired quantity of radiation suitable to a certain intercrop independent of palm density. If it

[2] For instance the extinction coefficient of the exponential Monsi–Saeki's model can be derived from radiative measurements.

[3] Previous observations in a coconut density trial in Côte d'Ivoire supported this statement (Girard, 1992).

could be ascertained that the practice had no long term detrimental effects on coconut yield then it could be adopted as one of the cultural management practices in an intercropping system.

Intercrop yield prediction can be assessed through the simulation of the PAR transmission as long as PAR remains the more limiting factor. This statement seems to be valid for the DRC intercropping experiments because there is no important water deficit at Davao and the competition for nutrients is minimized through the fertilization. Despite competitions for other resources than light can not be discarded, we can assume that predictions remain valid because the experimental corn and mungbean yield responses to the available PAR implicitly integrate these competitions.

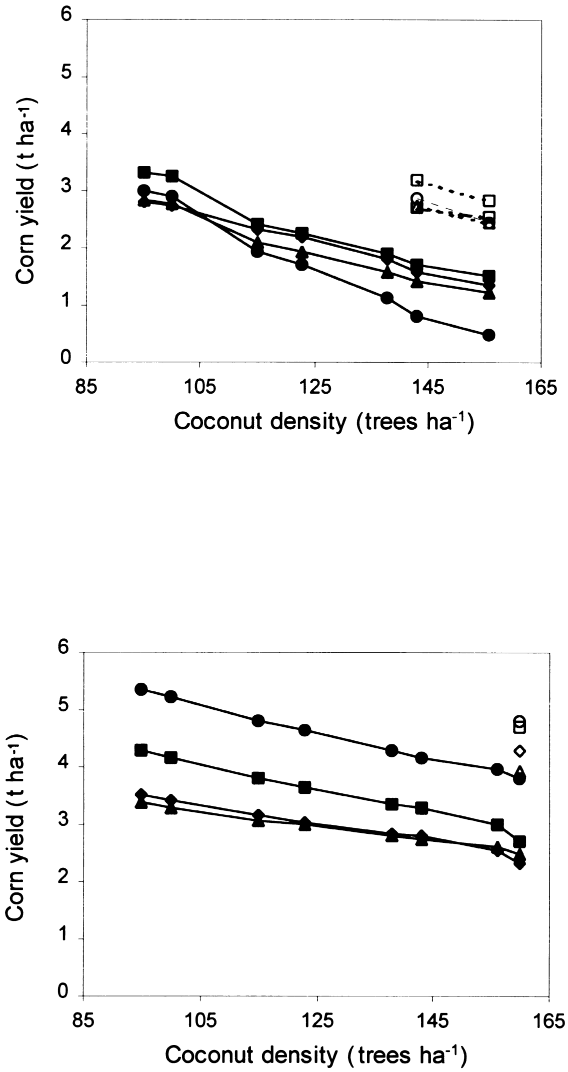


Fig. 10. Forecasted corn yields under 20 year (upper) and 40 year (lower) old coconuts at different densities. Same symbols as in Fig. 9, with open symbols representing pruned stands.

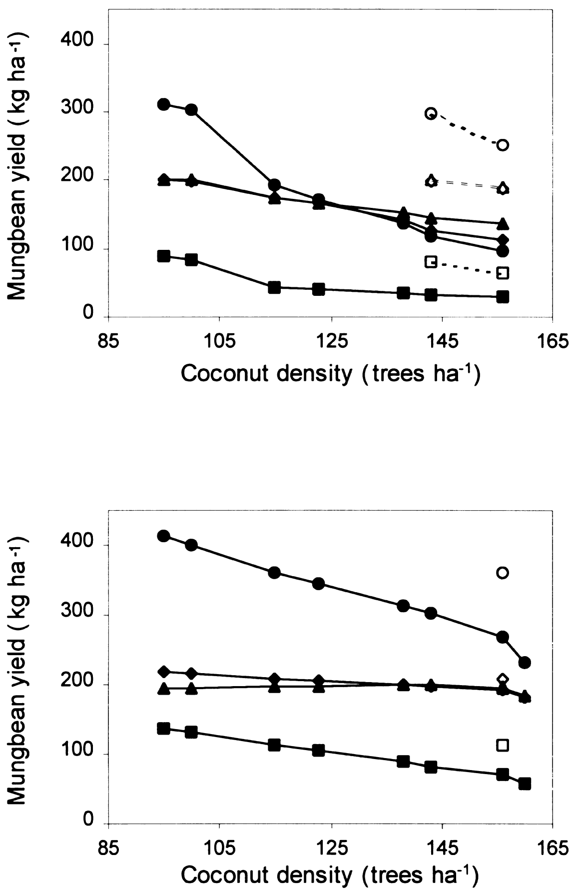


Fig. 11. Forecasted mungbean yields under 20 year (upper) and 40 year (lower) old coconuts at different densities. Same symbols as in Fig. 9 with open symbols representing pruned stands.

The generalization of the results presented herein requires further studies on coconut and intercrop materials. This is currently done within the frame of an EEC project[4]. Several coconut materials have already been studied, one at different densities in Côte d'Ivoire, one in south Sumatra and three in the Vanuatu. Analysis are presently done in order to assess the minimal set of architectural parameters needed to describe the trees, e.g. number of fronds

[4] Contract TS3-CT92-0132: Coconut Based Farming Systems.

per tree, frond length, number of leaflets per frond and length of the longer leaflet (default values being taken for other parameters). On the other hand, several intercropping experiments are conducted both in the Vanuatu and the Philippines. In the latter country, the behavior of crops is also studied under artificial shading in order to get their response to the PAR available in the absence of any competition with coconuts. Several varieties are tested because the response to the quantity of PAR varies strongly: the most productive variety in high light situations may not always be the best under deep shade (Bénard et al., 1996).

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