Agroforest Syst (2008) 72:63–74
DOI 10.1007/s10457-007-9068-3

Using 3D architectural models to assess light availability and root bulkiness in coconut agroforestry systems

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Received: 14 June 2006 / Accepted: 16 May 2007 / Published online: 20 June 2007

Abstract *Using 3D architectural models to assess light availability and root bulkiness in agroforestry systems*. In many parts of the humid tropics, coconut trees are frequently intercropped with food crops, or tree crops such as cocoa. The performance of such systems depends on planting patterns, but also on growing conditions for crops below the coconut canopy throughout the development of the coconut trees. We used a modelling approach providing indicators for assessing above-ground competition for light and below-ground competition for space, in order to optimize intercropping in coconut smallholdings. Light transmission and the number of coconut roots in the interrow were assessed in coconut smallholdings from 6 to 60 years old. The modelling of light transmission through coconut stands was based on three-dimensional virtual coconut trees and a numerical light model that computed the shade cast by coconut trees on underlying crops. Root colonization in the interrow was assessed with virtual 3D coconut root systems. Our results showed that intercropping with shade-tolerant species was not limited by light transmission from the 35th year after coconut tree planting. However, at that stage of coconut tree development, the density of primary roots in the interrow limited intercrop development, especially for root and tuber crops. Alteration of the planting pattern over time increased light transmission but did not significantly affect root density. This modelling approach, which involved little parameterization that was easily done, appeared to be an efficient tool for recommending coconut tree planting patterns and densities, as well as indicating intercrop potential depending on their location in the most sunlit areas with minimum root competition.

Keywords Above- and below-ground competition · *Cocos nucifera* L. · Cropping system · Light partitioning · Root colonization · Vanuatu

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Introduction

Coconut trees (*Cocos nucifera* L.) are cultivated on around 12 million hectares worldwide. It has been estimated that they directly involve more than 10 million households (i.e. around 50 million people) (Persley 1992). In tropical Asia and Oceania, the main regions producing copra (dried coconut meat), most of the production comes from family type smallholdings (Nair 1983). In those smallholdings, coconut trees are grown along with other species, both food crops (*Musa* spp., *Manihot esculenta*, *Discorea* spp., *Xanthosomas sagittifolium*), and cash crops (e.g. *Theobroma cacao*, *Coffea* spp.) (Nair 1983; Das 1999). Those intercrops are mostly grown during the first 5–7 years, corresponding to the coconut tree juvenile period, and help to compensate for the absence of income during the coconut unproductive period (Ollivier and Daniel 1994; Bonneau and Sugarianto 1999; Das 1999). As coconut trees develop, particularly with the expansion of their crowns in the productive period, light conditions become limiting for intercrop development and performance (Nair 1979). In Vanuatu (Melanesia), some hardy species, such as *Musa* spp. or *Abelmoschus manihot*, are nonetheless sometimes grown inside old plantations. In that case, those species are grown in gaps in the planting design resulting from the death of one or more coconut trees, or on the edge of plots (Lamanda et al. 2006).

In coconut smallholdings, as is generally the case in agroforestry plots, the performance of the different stands depends on the degree of competition between and within species, either above-ground (competition for space and photosynthetically active radiation: PAR) or below-ground (competition for space, nutrients, water). Moreover, the different types of competition evolve as the years goes by, over long time spans, as the biological cycle of the coconut tree lasts for around 80 years. Competition for above-ground and below-ground resources, and its variation during coconut tree development, have mostly been studied in coconut estates, and only few authors (Nair 1979, Ollivier and Daniel 1994, Nair 1983) have studied them simultaneously. Thus, using an estimation of ground cover by the canopies of coconut trees grown in an estate in India (Nelliat et al. 1974), Nair (1979) considered that the amount of radiation transmitted below the coconut cover would only substantially limit the development of intercrops during a period from 8 to 35 years after the coconut trees were planted.

Studies of coconut tree root systems have shown that the majority of coconut roots are located in the surface layers: 85% of roots are located in the layer from −30 cm to −120 cm (Nair 1979) and 67% of primary roots (RI: roots originating from the base of the coconut tree with a diameter of more than 5 mm, ensuring anchorage and extension of the plant's root system) are located in the first 60 cm of soil (Colas 1997). In addition, coconut roots are mostly located within a radius of 2 m around the base of the stem, according to Kushshaw et al. (quoted in Nelliat et al. 1974), and Anilkumar and Wahid (1988). Consequently, the root systems of coconut trees and of intercropped species would, according to those authors, not overlap, and would not therefore limit intercrop development (Nelliat et al. 1974 and Nair 1983). However, under the conditions in Vanuatu (Melanesia), the root systems of intercropped coconut trees and cocoa trees, without any soil tillage, intertwined from the 4th year onwards (Colas 1997). Those observations were subsequently confirmed in numerous intercropping situations and under varied soil and climatic conditions (Jourdan, pers. com.). Primary root (RI) growth is continuous and mortality limited, so RI extension continues throughout coconut tree development (Colas 1997). Consequently, the RI network could be a physical obstacle to intercrop development and production, in the surface layers, by limiting the volume of soil available. Through all their different branchings (secondary, tertiary and quaternary roots), they could also limit the resources available for use by intercrops (Colas 1997).

Those results only involved estates, and the development of competition for above-ground and below-ground resources in coconut smallholdings is currently unknown. In particular, it is not known how radiation transmitted below the canopy changes, or how RI soil colonization is modified during coconut tree development in smallholdings, where the coconut trees are grown with no soil tillage and without chemical inputs.

In order to improve intercropping in smallholdings, we sought to find out at what moment in the cycle and at what place in the plot environmental conditions were compatible with intercropping, in line with threshold values for (i) the rate of incident radiation transmission and (ii) the rate of soil occupation by coconut roots in the surface layers. A modelling approach was undertaken to characterize the spatio-temporal changes in 6–60-year-old coconut stands of both Photosynthetically Active Radiation (*PPFD* = PAR Photon Flux Density) transmitted below the canopy formed by the coconut palms, and the density of coconut RI. The distribution of PAR transmitted below the coconut storey (*PPFDt*) and the distribution and density of RI were estimated using 3D architectural representations of coconut trees. The consistency of both models over a chronosequence of plots representing the development of coconut trees in smallholdings was first checked. Virtual experiments were then conducted to assess the possibilities for intercropping depending on the age of the coconut stand in regular and thinned planting patterns. Lastly, based on those results, we identified the characteristics of species suitable for intercropping in coconut plots and go on to discuss the relevance of the models used to assess the possibilities of intercropping in coconut smallholdings.

Material and methods

Field measurements

Experimental designs

Plots were selected on the plateau of the island of Malo (15°40′S; 167°10′E), which has the same pedoclimatic conditions as the east of the island of Santo (Quantin 1982), where the VARTC (Vanuatu Agricultural Research and Training Centre) research station is located, and where most references for coconut trees growing in Vanuatu have been established (Coulon et al. 1983; Labouisse 2004; Labouisse et al. 2004).

The soils of the Malo plateau and the east of Santo are Inseptisol Eutrudepts according to the ‘‘Soil Taxonomy’’, 1998. The soil profile is relatively uniform over 2–2.5 m in depth down to a coral limestone bedrock: silty clay and 5–10% humus-bearing horizon on the surface (0–20 cm), somewhat clayey with little humus (1%) deep down resulting in root distribution without any major constraint down to the limestone bedrock (Quantin 1976). These soils are considered very fertile with a high water-holding capacity and a high cation exchange capacity. The rather low macroporosity beneath the humus-bearing horizon is the greatest constraint limiting soil suitability (Quantin 1976).

The climate is of the humid equatorial type (Quantin 1982). Average rainfall is 2870 mm per year, with a regularly distributed rainfall pattern, and a less rainy season from June to August. The average temperature is 24.7°C with slight variations over the year. The relative humidity is high, varying between 85 and 90% over the year (Quantin 1982).

Eleven smallholder plots, representing a chronosequence of coconut tree development between 6 and 80 years after planting, were selected on the plateau of the island of Malo. The plots, corresponding to 68–78-year-old coconut plantations, were located more along the edge of the plateau, on a shallower soil. All plots had a planting density of 150 ± 30 coconut trees per ha, in a more or less 8 m × 8 m square design. The planting material was of the ‘‘Vanuatu Tall’’ type (VTT), planted after gradual clearance of secondary forest. During the coconut tree juvenile phase, food species such as *Xanthosomas sagittifolium*, *Discorea nummularia*, *Musa* spp., *Carica papaya* were intercropped with the coconut trees. The coconut trees were also intercropped with different woody perennial species, most frequently *Mangifera indica, Barringtonia edulis, Hibiscus tiliaceus*. Twelve different woody species per plot on average were inventoried in the chosen plots.

Measurement of PAR under coconut tree cover (PPFDt)

The incident PAR transmitted below the coconut storey (*PPFDt*) was estimated from hemispherical photos, taken for 3 replications of the grid of the elementary planting design in each of the selected smallholder plots. For each mesh of the planting design, 9 photos were taken in order to take into account *PPFDt* variability within the motif (Fig. 1a). The hemispherical photos were taken with a digital camera (Nikon, coolpix 4500) fitted with a fish-eye lens (Nikon, FC-E8). The images were processed by Gap Light Analyser free software (GLA; Frazer et al. 1999), which was used to estimate the average annual rate of incident radiation transmission for a clearness index[1] fixed at 0.5.

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[1] The ‘‘clearness index’’ (Erbs et al. 1982) corresponds to the ‘‘cloudiness index’’ of the GLA software developed by Frazer et al. (1999).

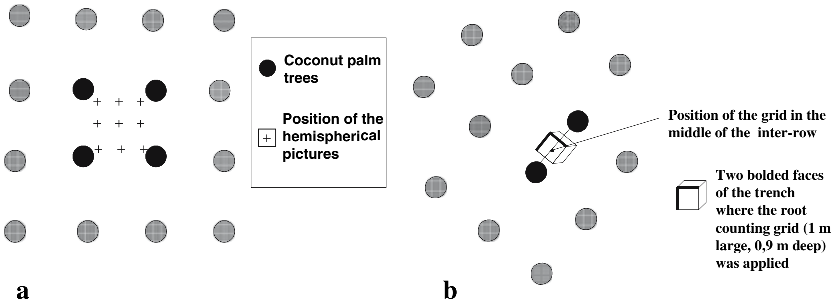

Fig. 1 Measuring system in VTT (Vanuatu Tall) coconut smallholdings (**a**) measurement of PAR Photon Flux Density (*PPFDt*) by hemispherical photos and (**b**) measurement of NIRP (average number of coconut primary root impacts in the middle of the interrow) and of primary root density from a grid positioned on the 2 adjacent sides of a pit dug in the middle of the interrow. The coconut trees were planted in an 8 m × 8 m square design

Measurement of interrow colonization by coconut tree primary roots (RI)

Soil occupation by coconut roots was characterized by counting RI impacts on vertical soil profiles in the middle of the interrow (*NIRP*). The number of RI was selected as an indicator of the level of spatial occupation (on the understanding that RI did not provide any indication of the degree of competition for water and mineral nutrient uptake, such functions being ensured by fine roots). The number of RI impacts (*NIRP*) corresponded to the mean of the number of coconut RI impacts counted using a grid measuring 0.9 m high by 1 m wide, with a mesh of 10 × 20 cm. A 1 m^3 pit was dug in the interrow, the measurement grid was successively positioned against each of the 2 adjacent vertical walls of the pit (irrespective of direction) and the coconut RI were counted (Fig. 1b). Those measurements were taken in 4 of the 11 selected plots (plots 5, 8, 35 and 68 years old).

Computation of virtual coconut stands for radiative computations

Virtual VTT coconut trees were simulated using the methodology and software described in Dauzat and Eroy (1997) for the simulation of light transmission using 3D coconut stand representations. Re-parameterizing of architectural mock-ups for the VTT variety was carried out in Vanuatu, in the VARTC research station plantations. Following observations by Mialet et al. (2001) a simplified measurement protocol was adopted, based on the following parameters: (i) stem height, (ii) the number of green fronds in the crown (iii) the length of frond rank 14[2] (iv) the number of leaflets on frond rank 14, (v) the length of the leaflets and (vi) the area of the leaflets. Measurements were taken on 10 coconut trees aged 6 and 20 years, and on 5 coconut trees aged 35 years.

The architectural parameters of the 60-year-old VTT coconut trees were estimated by extrapolating the data obtained for the previous ages, and from data given by Silva and Abeywardena (1970) regarding (*a*) stem height, (*b*) the length of rank 14 fronds, and (*c*) the maximum length of Tall coconut tree leaflets. After checking the coherence between the measured data and Silva and Abeywardena's data (1970) for parameters *a*, *b*, and *c*, allometric relations were established in order to predict changes in each of the parameters depending on the age of the VTT coconut trees. With the exception of parameters *a*, *b* and *c*, the architectural mock-ups of the 60-year-old VTT coconut trees were produced with architectural parameters identical to those established for 35-year-old VTT coconut trees.

In compliance with smallholder practices, the virtual representations of the coconut trees were positioned in a square planting design 8 m apart (i.e. a planting density of 156 coconut trees ha^{-1}). For each coconut stand age (6, 20, 35 and 60 years), a plot of 9 coconut trees was generated for radiative computations, each coconut tree being different, owing to the

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[2] Frond ranks are noted and identified according to the regular phyllotaxy of the coconut tree: frond 14 corresponds to the frond supporting nuts the size of a fist, and is located directly beneath the inflorescence.

stochastic computation of observed variability. For the 60-year-old coconut stand, we also computed a scene representing the planting design altered by the disappearance of a coconut tree. In all cases, given the toricity option used for the computations, each plot had to be considered as one mesh in an infinite cover.

Computation of PAR transmission below coconut stands

Radiative computations were performed using Archimed[3] models described in Dauzat et al. (2001) which had been validated on coconut stands by Dauzat and Eroy (1997) and Mialet-Serra et al. (2001). The transmission of incident PAR under virtual coconut stands was computed with the MIR model using a toricity option such that elementary plots were virtually replicated to infinity. PAR multiple scattering by the soil and coconut trees was simulated by the MUSC model (Dauzat and Eroy 1997). In order to obtain the complete radiative balance, the results of the two models were combined for theoretical radiative conditions defined by the clearness index (Erbs et al. 1982). All the virtual experiments presented in this paper were run for a clearness index of 0.5. The PAR scattering factor for coconut tree crowns (reflection + transmission coefficients of fronds) was set to 0.25 and the reflection coefficient for soil to 0.18 for the computation of *PPFDt,s* which represented the total PAR (including scattered radiation) available for intercrops. For a comparison of GLA computations of *PPFDt* outputs restricted to the incident PAR fraction hitting the soil, multiple scattering was ignored. Alternatively, scattering was set to zero for computing *PPFDt* consistently with GLA outputs that did not account for scattered radiation. All results were expressed as percentages of incident *PPFD* above the canopy.

Computation of soil occupation by coconut tree horizontal primary roots (RI)

The RACINES model was originally developed for 3D computation of the oil palm root system architecture, along with its development over the first 20 years after planting (Jourdan and Rey 1997a; b). The model was adapted to compute the root system architecture of VTT coconut trees, along with its development over the first 25 years after planting (Colas 1997). To reduce the calculation time required for the computations envisaged in this study (computation of 60-year-old plantations), the RACINES-coconut model was considerably simplified in topological structure (size of the virtual internodes increased, change in calculation time step from day to year, elimination of vertical RI not competing in the interrow, elimination of branchings, elimination of root types only existing in the juvenile stages), and in root axis geometry (tortuosity index and simplified Young modulus). The dynamic parameters for RI growth (growth rate, emission rhythm, death and pruning probabilities) were also modified and a sensitivity analysis was performed. It was thus possible to considerably reduce the digital size of the mock-ups, enabling rapid computation of virtual plantations older than the age corresponding to the economic optimum of oil palm plantations for which the model had originally been programmed. The mock-ups therefore only represented sub-horizontal roots over 5 mm in diameter, i.e. sub-horizontal RI likely to limit intercropping in coconut smallholdings, particularly with tuber and root crops.

In order to adjust the resulting simplified RACINES-coconut model, it was necessary to parameterize the architectural mock-ups corresponding to adult VTT coconut tree root systems. To do that, we used measurements taken in a VARTC plantation to determine the maximum length of RI on 35-year-old VTT coconut trees. The simplified RACINES-coconut model was calibrated by comparing the number of computed RI impacts—on a virtual measurement grid positioned in the middle of the interrow (4 m from the base of the coconut trees)—with the number of impacts actually counted in the 35-year-old VTT plantation at VARTC (as described earlier). Once calibrated, the simplified RACINES-coconut model was only given the age of the coconut trees and their planting design to generate, by computation, a 3D representation of the horizontal RI architecture of the coconut trees.

To compute RI distribution when the planting design was altered (e.g. after some of the coconut trees died), we assumed, based on relative observations

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[3] The ‘‘ARCHIMED’’ simulation platform brings together the MIR and MUSC radiative models plus micrometeorological and ecophysiological modules for simulating transpiration, temperature and photosynthesis within plant stands (Dauzat et al. 2001).

of the speed of coconut RI decomposition in the VARTC plantations, that the RI of the missing coconut tree would decompose in less than a year under the conditions in Vanuatu (Jourdan, pers. com.). The altered design therefore corresponded to a complete design in which the roots of the missing coconut tree (central coconut tree) had completely disappeared.

The distribution of VTT coconut tree RI was computed on a scene comprising 30 coconut trees planted in an 8 m × 8 m square, corresponding to a complete design, i.e. a density of 156 coconut trees per ha for coconut trees aged 6, 20, 35 and 60 years. For the 60-year-old VTT coconut trees, we also computed the distribution of coconut RI for an altered design (previous scene modified by the disappearance of the central coconut tree).

Results

Average variation in *PPFDt* in smallholdings

The variation in *PPFDt* estimated from hemispherical photos exhibited an exponential increase during coconut tree development in smallholdings ($R^2 = 0.93$, Fig. 2). The average *PPFDt* values obtained per computation using architectural mock-ups that had been re-parameterized for plantations aged 6, 20 35 and 60 years corresponded to a trend in *PPFDt* change that was coherent with the change characterized in smallholdings.

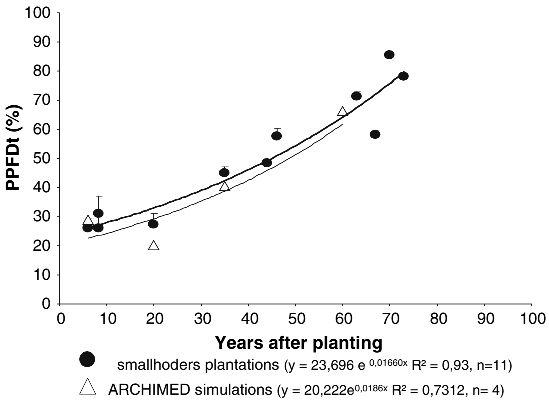

Fig. 2 Variation in the incident radiation transmission rate ($PPFD_t$) in coconut smallholdings vs the years after planting

After the first ten years, corresponding to the coconut tree juvenile phase, *PPFDt* increased regularly in line with coconut tree age; at around the 10th year, 30% of average *PPFDt* was transmitted below the cover, by the 45th year 50% of *PPFDt*, and after 60 years *PPFDt* reached values of around 65% (Fig. 2). However, those average *PPDFt* values sometimes masked heterogeneity in radiation distribution due to the macro-structure (planting design) and micro-structure (architecture of the individual coconut trees) of the stand, which it was important to have access to, in order to consider the possibilities for intercropping under coconut trees.

PPFDt distribution within plots during coconut tree development

During coconut tree development, stem height increased and the architecture of the leaf crown was modified (reduction in the number and length of fronds, reduction in the maximum leaflet length on the fronds, and reduction of the petiole:frond length ratio) (Fig. 3). The percentage of soil coverage by the leaf crowns evolved accordingly, increasing from 66.6% at 6 years after coconut tree planting to 73% at 20 years, then decreased, amounting to 47.8% of the area of the scene 35 years after planting, finally reaching values of around 20.1% 60 years after planting (Fig. 4–1). According to Bellow and Nair (2003) the range between 40% and 60% of *PPFDt* is currently considered to be optimum for the development of shade-tolerant species, under most conditions. Six and twenty years after coconut planting, *PPFDt* appeared on average to be under 40% and distributed relatively uniformly over the entire scene. Thirty-five years after planting, *PPFDt* reached an

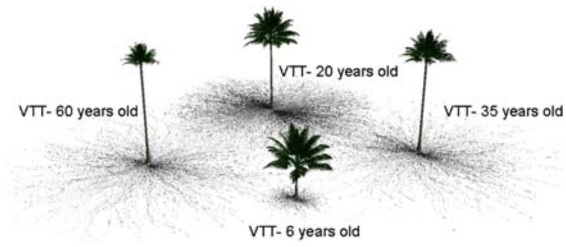

Fig. 3 Aerial view of architectural mock-ups re-parameterized for the above-ground and below-ground parts of Vanuatu Tall (VTT) coconut trees aged 6, 20, 35 and 60 years, under the conditions in Vanuatu

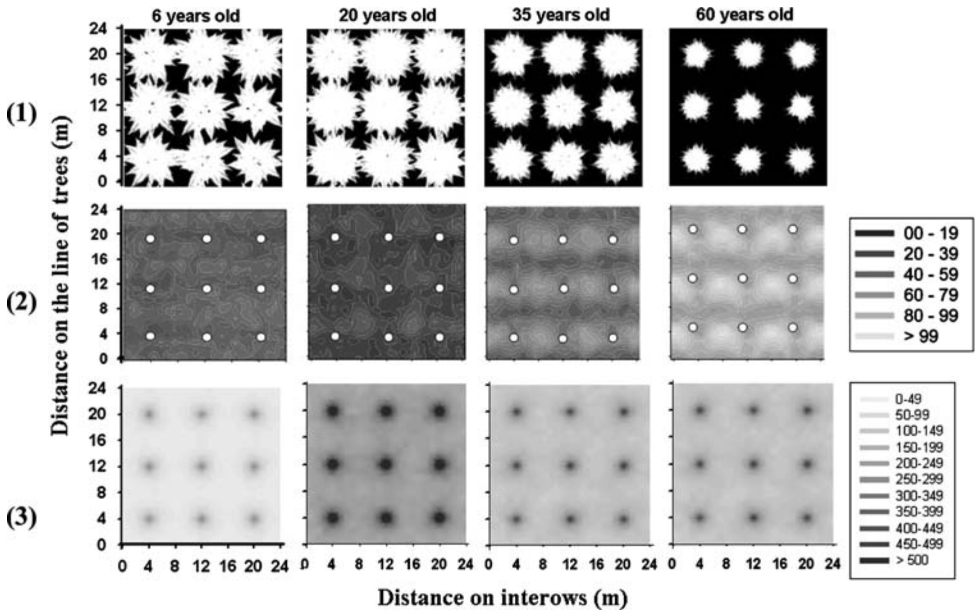

Fig. 4 Variation (1) in soil cover by VTT (Vanuatu Tall) coconut crowns, (2) in *PPFDt* (PAR Photon Flux Density transmitted) distribution and (3) in NIRP (average number of coconut primary root impacts in the middle of the interrow) during coconut tree development (a = 6 years, b = 20 years, c = 35 years, d and e = 60 years)

average value of 40.6% but distribution was heterogeneous. Zones could be distinguished, located between the coconut trees (the total area of which corresponded to 46.6% of the area of the scene) where *PPFDt* was equal to or greater than 40% and which would be suitable for the development of shade-tolerant species. *PPFDt* was under 40% in the rest of the scene. Changes in the architecture of the coconut trees as they developed might explain the distribution of *PPFDt*: the span of the crown (with the reduction in frond length) decreased as the coconut trees grew older, enabling better *PPFDt* transmission below the cover. At 60 years, *PPDFt* reached an average value of 65% with less heterogeneous distribution (variance 68% as opposed to 71% at 35 years); as the coconut trees were taller, the movement of shadows over the ground during the day tended to homogenize *PPFDt* distribution. It was then possible to distinguish two zones: (1) between the coconut tree rows, *PPFDt* was around 60%, suitable according to Bellow and Nair (2003) for the development of shade-tolerant species and (2) between the coconut trees where *PPFDt* was around 80%. Note that at the centre of that zone, which would be suitable for the development of shade-intolerant species, virtually all the *PPFD* reached the ground (*PPFDt* > 80%) (Fig. 4–2, a, b, c, d).

Dynamics of interrow colonization by coconut tree primary roots (RI) in smallholdings

Most of the RI were found in the first 40 cm of soil, irrespective of the coconut tree development stage (Fig. 5a). Colonization of the interrow by coconut primary roots did not begin until the sixth year after the coconut trees were planted: there was only one root in the middle of the interrow for 6-year-old smallholdings (Fig. 5a). Colonization of the interrow evolved as the coconut trees developed, reached a maximum under smallholder conditions around 35 years after the coconut trees were planted, then decreased. *NIRP* decreased from 50 for 35 years after coconut tree planting, to 13 for 68 and 78 years after coconut tree planting. The absence of roots below a depth of 60 cm for the 68 and 78-year-old smallholdings was explained by shallower soil in those plots than in the plots representing the earlier stages of coconut tree development. All in all, observed data in smallholdings and computed data gave similar root profiles (Fig. 5b). Computation of 20-year-old

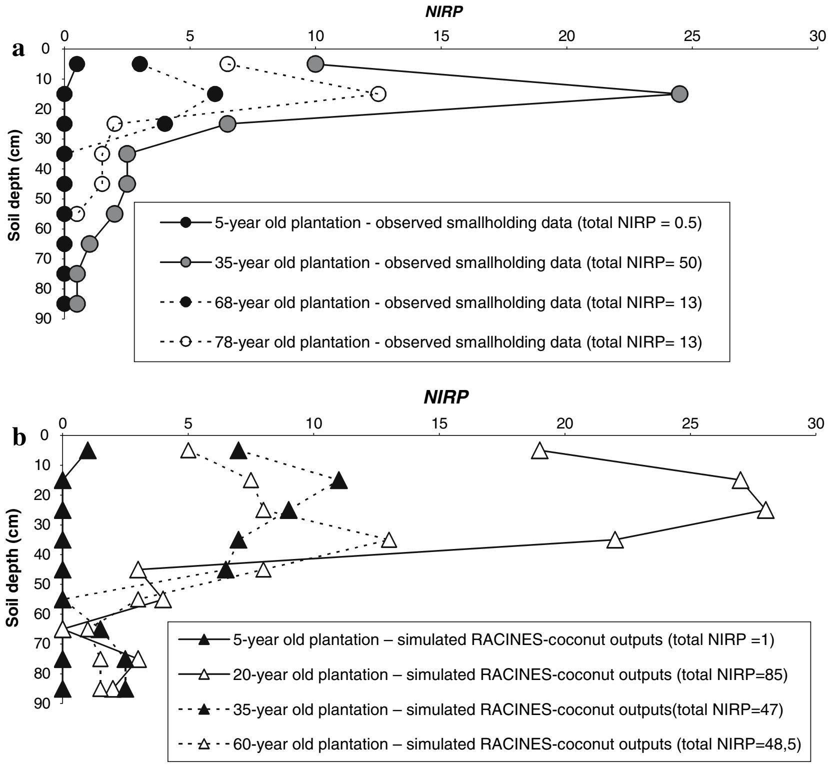

Fig. 5 Variation in the number of primary roots in the middle of the interrow (*NIRP)* during coconut tree development (**a**) *NIRP* measured in smallholder plots and (**b**) computed with the RACINES-coconut model. *NIRP* = average number of coconut primary root impacts counted per 10-cm horizon on the 1*0.9 m grid positioned in the middle of the interrow (≈ 4 m from the base of the coconut trees)

plantations revealed maximum root colonization in the interrow, and in the first 40 cm, which was greater than that indicated by observations in 35-year-old plantations.

Distribution of RI soil occupation in plots during coconut tree development

Six years after coconut tree planting, the RI did not reach the interrow (Fig. 4–3a). Colonization of the interrow by RI seemed to be maximum 20 years after planting in the model. It then decreased, with the RI network in the interrow appearing less dense 35 years and 60 years after planting (Fig. 4–3). From the 20th year after coconut tree planting, there was intertwining of the horizontal RI over the entire computed scene (Fig. 4–3). The RI impacts on the virtual grid positioned in the middle of the interrow proportionally only occupied a very small part of the space, irrespective of the coconut tree development stage: at 6 years = 0.1 RI/dm^2, at 20 years = 10.8 RI/dm^2, at 35 years = 4.7 RI/dm^2 and at 60 years = 4.85 RI/dm^2.

Effect of an alteration in the planting design on *PPFDt* distribution within plots and on soil occupation by RI

When the planting design was altered by the death of a coconut tree, the average *PPFDt* value (69.6%) was increased by 3.3%. *PPFDt* was then more than 60% over 89.3% of the total area of the scene, i.e. a 15% larger area compared to the unaltered design. In addition, *PPFDt* was more uniform (the variance of *PPFDt* on the scene with the altered design was 60% as opposed to 68% with a complete design) and its distribution was modified (Fig. 6). The limits of the zones established for the regular design were changed (Fig. 6); the maximum sunlit zone (where *PPFDt* > 80%) increased by 4% corresponding to the elementary areas between the two coconut trees next to the missing one.

However, alteration of the design did not have any significant consequences for soil occupation by RI. Although the number of RI impacts (*NIRP*) in the middle of the interrow decreased with the alteration in the planting design (from 48.5 *NIRP* with the

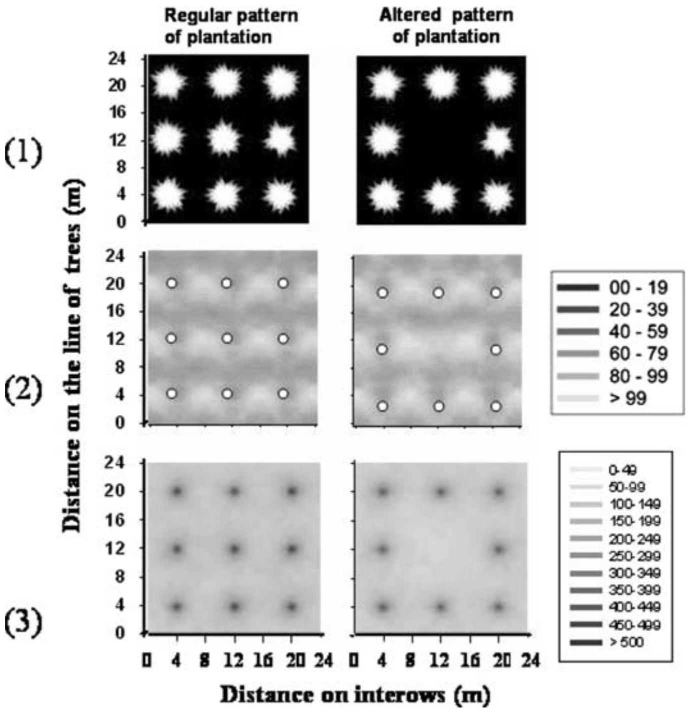

Fig. 6 Effect of the alteration of the planting pattern on (1) soil cover by the VTT coconut crowns, (2) PAR Photon Flux Density (*PPFDt*) distribution and (3) NIRP (average number of coconut primary root impacts counted per 10-cm horizon on the 1*0.9 m grid positioned in the middle of the interrow)

complete design to 39.5 *NIRP* with the altered design), occupation of the below-ground space was still substantial (Fig. 5–3 e and d), and the space freed by the death of the missing coconut tree's root system was apparently rapidly colonized by the neighbouring coconut trees. Field observations tended to back that hypothesis, which has yet to be demonstrated.

Discussion

Changes in the *PPFDt* measured in smallholdings were consistent with the model for changes in radiation transmission through the canopy proposed by Nelliat et al. (1974). However, the values measured in smallholdings and those that were computed were globally higher than those proposed by Nelliat, since the planting design considered was less dense and the planting material was different. Using the threshold values proposed by Nair and Bellow (2003), intercropping with shade-tolerant species appeared to be possible from the 35th year after coconut tree planting. However, at that stage of coconut tree development, our observations indicated that RI had colonized the interrow. Although root density was low, the RI network observed at a depth of 90 cm nonetheless appeared to be dense and would consequently be a physical obstacle to the development of the underground organs of intercrops located in the interrow. Our observations differed from those carried out in plantations in India, where it was found that the root system was located in a 2-m radius around the coconut stems (Nelliat et al. 1974; Nair 1983, 1979; Anilkumar and Wahid 1988). Soil tillage, such as passing with cutting tools (disc plough, which would cut the roots) in the Indian plantations, might explain why roots were confined to a 2-m radius around the stem (Rognon and Bonneau, pers. com.) and the difference with our results obtained in plantations without soil tilling instruments. In Vanuatu, coconut palms and intercrops are planted by using a stake or a shovel to make a hole the size of the plant it has to take.

3D models that can be used to easily carry out virtual experiments, which would otherwise require unwieldy and very costly experimental designs (de Reffye et al. 1995) offer a useful way of more effectively determining the feasibility of intercropping in coconut plantations. As knowledge stands at the moment, it seems too early to expect a model of coconut tree development integrating the factors that influence it throughout the coconut tree growing cycle (practices, pedo-climatic conditions, regulation between the above-ground and below-ground parts of coconut trees). We therefore felt it would be more pragmatic to locally re-parameterize the models that exist for above-ground and below-ground parts of coconut trees and combine their output to gain a clearer understanding of the opportunity for intercropping in coconut plantations. This approach can be transferred to other situations (different agroecological conditions and/or variety and/or coconut tree development stage). That merely calls for relatively simple re-parameterization, though improvements for the parameterization of each of the models can be envisaged.

A set of 6 parameters defined from the simplified protocol established by Mialet-Sera (2001) was used to parameterize the architectural mock-ups for the VTT coconut variety. Of those parameters, (i) stem height, (ii) the number of fronds in the crown, (iii) the length of frond 14 and (iv) the length of the leaflets, appeared to be sufficient for re-parameterizing the architectural mock-ups. Measurement of those parameters, which did not require any particularly technical equipment or skills, was easily possible to re-parameterize the mock-ups corresponding to the architecture of the coconut trees. But parameterizing the angle of frond slope in the crown would have provided a more truthful representation of crown architecture. One way of regaining access to that parameter, which is difficult to measure, might be to adjust the inclination of the lowest fronds, using photographs of isolated coconut trees.

The 3D virtual coconut trees were indirectly validated against the PAR transmission rate (*PPFDt*) simulated with Archimed or measured from hemispherical photos. A more direct validation could have be carried out by comparing computed and measured gap fractions. However, insofar as sky luminance is calculated in a similar way by Archimed and GLA software, validation against *PPFDt* was also an overall validation of the simulated gap fractions. Further checking of directional gap fractions could nevertheless be carried out by simulating hemispherical photos within the virtual stands.

Parameterization of the RACINES-coconut model needed 3 parameters that were necessary for satisfactory calibration of the model in a new situation. For coconut tree ages, it seemed enough to calculate (i) the rate of primary root emission, (ii) the horizontal RI:vertical RI ratio and (iii) to observe the maximum RI length. In our case, with the simplified RACINES-coconut model, only the last parameter was necessary for re-parameterizing the digital mock-ups. Our representation of the root system was incomplete with no vertical roots and only with RI, so it was only a tool for representing soil colonization by horizontal RI between coconut trees in a given planting design. In addition, in order to interpret the degree of root system development in functional terms, particularly for the level of competition for water and nutrients, it would be necessary to include medium and fine (absorbing) coconut tree roots in the representation.

Juxtaposition of the outputs from these 2 models, functioning independently and based on the calibration of architectural and root development mock-ups at a given moment in the coconut tree development cycle, did not account for interactions between the above-ground and below-ground sections and their dynamics. Moreover, for the root model, the parameters of the growth, mortality, branching and root production laws took into account competition between individuals within a plantation, but did not incorporate any sudden change in that competition (e.g. wind damage, water stress). Lastly, another limitation of the root model was that it did not take into account any change in the substrate (physical and chemical properties of the soils fixed at the outset and assumed to be constant throughout the growth cycle).

Nevertheless juxtaposition of the outputs from both the ARCHIMED and the RACINES-coconut models provided some spatialized indicators of above-ground (*PPFDt*) and below-ground (*NIRP)* constraints for intercropping. In particular, by showing interrow colonization by coconut RI, the reason why farmers did not grow tubers in their bearing coconut plots became obvious. The death of a coconut tree and the decomposition of its RI did not appear to generate sufficient room for tuber development[4]. Conversely, coconut trees are frequently intercropped with cocoa, a species for which the optimum *PPFDt* range is

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[4] These biophysical reasons may be completed by cultural considerations: in Melanesian societies, the endemic tuber plants *Colocasia esculenta* and *Discorea* spp. and the coconut plantations developed during the colonial period each have a distinct social status and, in that respect, they are barely combined in the same space (Caillon 2005)

around 40%, corresponding to the average *PPFDt* values characterized by bearing coconut plots. In addition, cocoa trees have a taproot system, which, according to Colas (1997), would limit competition with coconut RI for space below ground and competition for water use by the two species.

By incorporating the *PPFDt* and *NIRP* spatialized indicators in a local and targeted agronomic assessment, it was possible to select the species to be intercropped with coconut trees and define their optimum positions. Characterization of the spatialized indicators (*PPFDt* and *NIRP*) made it possible to spot structural characteristics (theoretically marking a type of ecological functioning) that appeared to be compatible with the constraints identified in coconut plantations. The following (structural) characteristics could thus be adopted to choose species to be intercropped with coconut:

(i) shade-tolerant species for zones with a *PPFDt* between 40 and 60%, and more *PPFDt*-demanding species for zones with a *PPFDt* over 60%,

(ii) species with a taproot architecture more than bunched roots, exploring soil resources below the first 40 cm of soil, in which a high density of coconut primary roots is found, useful aerial production rather than root production, as tuber development and yields can be limited by intertwining of RI. Tubers such as taro, yam, cassava, kava, etc., are therefore not recommended in this type of intercropping unless the number of coconut trees is reduced.

Identification of these structural characteristics is therefore an initial stage in choosing species to be intercropped with coconut trees and determining their position in bearing plots. However, before recommending any extension of these intercropping combinations, they need to be tested (i.e. quantify the development and performance of the chosen species in the selected positions), as doubt could be cast on the appropriateness of the combination by other factors not taken into account in the choices of species and their position resulting from 3D computations, such as competition for nutrients, invasion by weeds, the development of parasites or diseases, etc. In addition, before recommending these intercropping combinations, it would be essential to assess their profitability for farmers in the local socio-economic context.

Conclusion

The computations obtained with the ARCHIMED and RACINES-coconut models can easily be combined and can be used to quantify and locate above-ground constraints (*PPFDt*) and below-ground constraints (*NIRP*) during coconut tree development.

These models, which have been validated in diverse situations, are a cropping system design tool to be integrated into on-site agronomic assessments in order to (i) perceive the agroecological functioning of coconut-based farming systems, and (ii) select species to be intercropped and determine their optimum position in plots. These models can serve as decision-support tools, based on virtual experiments, in order to recommend new cultural techniques designed to minimize above-ground and below-ground constraints. It is then possible to assess interventions such as the pruning of lower fronds (Dauzat and Eroy 1997) or plantation thinning. One of the most interesting applications is for choosing the appropriate planting designs and densities for a given set of intercrops. These issues particularly occur for tree crops such as cocoa, whose performance needs to be assessed over several decades.

Considering both above-ground and below-ground constraints, we found that even if light transmission through the coconut canopy does not limit intercropping with shade-tolerant species from the 35th year after planting, soil colonization by RI constitutes a physical obstacle to the development of intercrops, especially of root and tuber crops. This led us to identify aerial production and tap root architecture as major criteria for selecting species to intercrop in coconut plantations.

Acknowledgements We should like to thank VARTC for its hospitality and logistics support, and the farmers of Malo for their warm welcome, and for providing access to their coconut plantations.

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