ATLANTIC ZONE PROGRAMME

Working Documents No. 12

SIMULATION OF SHADE PATTERNS:

A THEORETICAL APPROACH TO A PRACTICAL PROBLEM

C.J. Tazelaar

March 1991

CENTRO AGRONOMICO TROPICAL DE
INVESTIGACION Y ENSEÑANZA - CATIE

AGRICULTURAL UNIVERSITY
WAGENINGEN - AUW

MINISTERIO DE AGRICULTURA Y
GANADERIA DE COSTA RICA - MAG

CONTENTS

1 INTRODUCTION

Cocoa (*Theobroma cacao*) belongs to the the Sterculiáceae family. Its main centres of dispersion are the Amazonian and Central American lowlands. Actually the crop is grown in the mayority of tropical countries between 20° latitude South and 20° latitude North.

In the sixties and seventies the Centro Tropical de Investigacíon y Enseñanza (CATIE) in Costa Rica developed cocoa hybrids of the Trinitario type. Selection took place with emphasis on yield and resistance to the diseases black pod rot (*Phytophthora palmivora*) and ceratostomella wilt (*Ceratocystis fimbriata*). The hybrids were distributed in Costa Rica and other Central American countries. Expectations were high, but soon some mayor constraints were revealed: the yields were disappointing and the hybrids did not have tolerance to a new threat, the monilia disease (WAAIJENBERG & WESSEL, 1989).

Monilia, also called watery pod rot, is caused by the fungus *Moniliophthora roreri*, which attacks the cocoa pods in all stages of their development. At the end of 1978 the fungus was detected in the Atlantic Zone of Costa Rica. This year the annual production was about 10,300 tons of cacao. Within a few years production declined with 80-95 %. In 1983 Costa Rica produced no more than 1,850 tons (GALINDO & ENRIQUEZ, 1984). The disease caused the abandonment of many plantations and increased the labour costs in the few plantations which continued to produce.

To get a clear view of the factors limiting cocoa production in Costa Rica the Atlantic Zone Programme (CATIE/AUW/MAG) in 1989 started a detailed quantitative study on thirty farms in the Atlantic Zone. In regular field visits yield determining factors were assessed. During these field visits it was observed that the amount of shade had a pronounced influence on the growth of the cocoa crop (WAAIJENBERG & TAZELAAR, 1990; BUY & KOUWEN, 1991). The distribution of shade (trees) was very uneven, both between and within fields (Figure 1).

There exists little doubt about the importance of shade for the cocoa crop (Chapter 2). Many experiments have been carried out to determine the optimal amounts of shade, but much less is known about the optimal patterns of shade and the best plant arrangements, sizes and shapes of shade trees. Determining these parameters by means of field experiments would be very costly. Therefore the present study used a simulation programme developed by CATIE (QUESADA et al., 1987) to explore the spatial distribution of shade in relation with latitude, season, slope of the plot and arrangement and shape of the shade trees. The results may help to choose the species of shade trees and to determine their plant density and arrangement for specific conditions and so contribute to a more efficient use of shade trees and higher or more reliable crop yields. Although the study was started with cocoa in mind, the approach may be equally important for other tree crops grown under shade and for the analysis of light and shade patterns in multiple cropping systems involving tree crops.

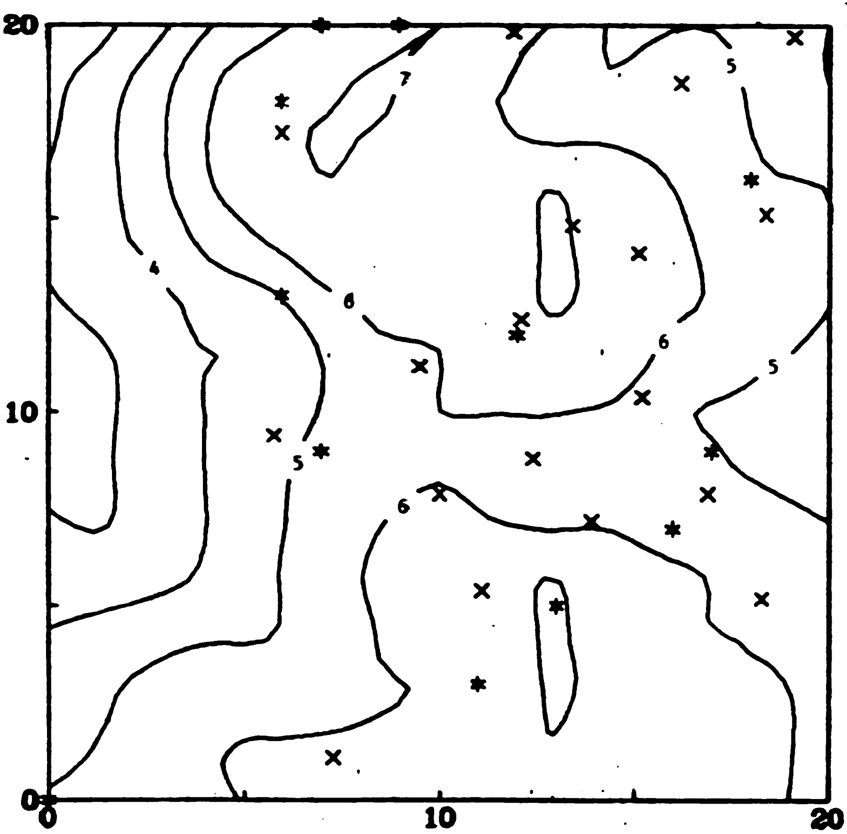


Figure 1. An example of the irregularity of shade in farmers' cocoa fields. The "x" indicate the positions of shade trees, the "*" those of cocoa trees. The lines connect points with an equal number of hours of shade (from 8.30 am to 15.30 pm).

2 THE FUNCTION OF SHADE

2.1 Cocoa and shade

In its natural habit cocoa (*Theobroma cacao*) is a small tree in the understory of the evergreen tropical rain forest. Shade is not only desirable in order to reduce excessive solar radiation, but also is important for the regulation of several ecological factors like soil fertility and moisture, wind speed, air and soil temperature, relative humidity, diseases, pests and weeds. With adequate fertilization and control of diseases, pests and weeds it is possible to obtain high yields without shade (WOOD, 1986). However, small scale farmers often cannot allow for such practices, especially when prices of cocoa are low. Therefore the use of shade trees and research on the optimal amount and distribution of shade remain highly relevant.

2.2 Physiological effects

The light intensity affects the size, thickness and chlorophyll content of leaves, which are larger and greener when grown under shade than when exposed to full sunlight. Young trees need a lot of shade, because radiation heats the leaves which causes closing of the stomatas leading to a reduced water transport, reduced photosynthesis and early fall of leaves. The amount of sunlight a young tree receives influences its growth in the way that trees receiving much sunlight get shorter internodes, more fan branches, a low jorquette and a dense crown, and thus a bushy appearance (WOOD, 1986). Young leaves are very sensitive to moisture stress and the growth of young cocoa plants is more vigorous when they are grown under shade, where relative humidity is high and air movement reduced. These conditions lead to a reduced evapotranspiration and prevent dehydratation.

The need for shade diminishes with age. A mature tree produces more leaves, which shade the underlying ones; this phenomenon is known as self shading. When adequate quantities of fertilizer are applied and shade is reduced or removed cacao production will rise as a result of increased photosynthesis. However, this cannot be maintained for a long period as it appears to reduce the economic life of the cocoa trees. Several soils of the survey area are chemically poor and few farmers apply fertilizer. Under these conditions about 50 % of shade is recommended, often without specifying what that means (CUNNINGHAM & BURRIDGE, 1960; ENRIQUEZ, 1985; EVANS & MURRAY, 1953; JIMENEZ, 1980; MARTINEZ & ENRIQUEZ, 1984; PURSEGLOVE, 1987; WESSEL, 1986).

2.3 Relation with diseases

There exists a relation between high precipitation and the incidence of Monilia. In a micro-climate with favourable conditions for the development of the fungus (high relative humidity and relative low temperature), as under dense shade, spore production will be high (LASS, 1986).

On the other hand, branches of cocoa trees exposed to full sunlight are severely attacked by dieback, a complex disease caused by capsids and fungus and related with low soil fertility, inadequate water supply and exposure to wind (KAY, 1961; LASS, 1986).

2.4 Characteristics of shade trees

Shade trees have been the object of several studies (ENRIQUEZ, 1985; MARTINEZ & ENRIQUEZ, 1985; WOOD, 1986). JIMENEZ (1980) and BEER (1987) made checklists of the desirable characteristics of shade trees.

The advantageous characteristics can be summarized as follows. Shade trees may facilitate crop management and have beneficial effects on the hydrological cycle. They protect the crop against pathogens, insects and adverse climatological conditions. They improve soil fertility and suppress weeds. When they have finished their job, they should be easily removed without damage to the cocoa trees. Preferently they should have an additional economic value.

The studies also mention some disadvantageous characteristics, such as extra labour requirements, hindering crop management, competition for light, nutrients and moisture and offering a refuge for insects and pathogens.

The lists appear to contradict each other when, for example, they state that shade trees both facilitate and hinder crop management. Usually there is some balance of positive and negative aspects, sometimes in favour of shade trees and sometimes against their use. On continuation some common shade trees of the Atlantic Zone of Costa Rica, and elsewhere, will be discussed.

Coconut (*Cocos nucifera*)

The use of coconut as a shade tree is widely spread. The palm is adapted to humid lowlands (up to 600 m) and its soil requirements resemble those of cocoa (ENRIQUEZ, 1985). When planted at 7.5 m x 7.5 m (175 palms/ha), the palms intercept about 44 % of the incoming sunlight. Coconuts have the advantage of transmitting more sunlight when they grow older (NAIR, 1979), which favours the cocoa crop. It has been observed that coconuts produce more in combination with cocoa than in pure stands. According to NAIR (1979) this is a result of the better development of the micro-organims living in the rhizosphere.

Laurel (*Cordia alliodora*)

This species has some very useful characteristics such as a rapid and erect growth, a deep root system, a small, open crown and easy natural regeneration. The tree is self-pruning and produces valuable timber (BEER, 1987). When harvested at an age of fifteen years the tree yields 200-300 m^3 wood/ha. Laurel is adapted to humid rain forest conditions up to 600 m above see level.

Poró gigante (*Erythrina poeppigiana*)

This species is widely used as shade tree. It is very easy to establish and can be propagated by seed or cutting. The tree is mostly planted at a distance of 12 m x 12 m. The tree grows very fast and its root system contributes to a better soil structure. Several other *Erythrina* species (like *E. berteroana*, *E. glauca*, *E. indica* and *E. velutina*) are also used as shade trees or in living fences.

Guabo (guavo) (*Inga* spp.)

Several *Inga* species are used as shade trees (SANCHEZ, 1983). They are easy to grow from seeds. Most have edible fruits (pulp) and the timber can be used as fuel. They grow fast and provide good shade after three years. The leaves fall all over the year, thus providing a continous supply of organic matter. The usual spacing is 10 m x 10 m.

Plantain and banana (*Musa* AAB and AAA)

They are widely used for tempory shade, because of their commercial value. They are planted at distances of 3 m x 3 m or 4 m x 4 m. Because of their superficial root system they compete with cocoa for nutrients and moisture. When permanent shade can be provided they are easy to cut, without much damage to the cocoa. On the other hand, under conditions of strong winds, poor drainage or high incidence of nematodes they are susceptible to lodging, which may damage young cocoa plants.

3 MATERIALS AND METHODS

3.1 Simulation methods

The patterns of shade in a field were simulated with a computer (PC/AT) programme of CATIE, "SOMBRA" (QUESADA et al., 1987). The programme allows for the calculation of hours of shade at specified coordinates (grid points) of a plot. The plot can be located at any latitude and may be horizontal or inclined and of variable size. Calculations can be done for any period of the year and solar movement can be simulated at any time interval. Different tree sizes and shapes can be defined. However, the larger the amount of data or the smaller the intervals simulated, the longer becomes the time needed for the calculations, which may be up to several hours.

The required inputs are (second column presents example):

- initial day of simulation (dd/mm/yy)	22/03/90
- final day of simulation (dd/mm/yy)	22/03/90
- periodicity of daily movement (days)	1
- latitude (degrees, minutes, north or south)	10,0,n
- start of daily simulation (hour, minutes)	9,0
- end of daily simulation (hour, minutes)	15,0
- periodicity of movement of the sun (minutes)	60
- type of plot (horizontal or inclined), maximal slope (degrees) and direction of the slope with regard to the north (degrees)	h,0,0
- dimensions of the plot and grid size (m, m)	30,35,0.5
- number of shade trees (n);	18
- characteristics of each shade tree: coordinates, form of the crown, height of the stem to the base of the crown, radius of the crown, height of the crown (all in m)	0, 0,5,6,4,4 0,16.67,5,6,4,4 0,33.33,5,6,4,4 ---and so on---
- print data matrix?	no
- print hours of overlap of shades?	si
- storage of output: disk, file, extension	c,rows,dat

The output is a three column ASCII file with:

- coordinates of each simulated point in the plot (m);
- total hours of shade received by each point (hours);
- total hours of overlapping shade in each point (hours).

The output of the simulation was processed (see Figure 2) with the LOTUS 1-2-3* programme into means and standard deviations (Table 2), plots (Figure 3) and histograms (Figures 5-9). The LOTUS file was used as input for the SURFER* programme, to make two- and three-dimensional plots of shade patterns (an example is presented in Figure 1). Only a small part of the plots could be reproduced within the limited space of this paper.

The gross plot size was set at 30.5 m x 30.5 m; net plots were 20.5 m x 20.5 m (note that the dimensions in the input of the programme refer to the distance between the first and last grid point). The 5 m wide borders were needed to eliminate the effect of diagonally incoming sunlight which would cause an underestimation of the amount of shade. The grid size was set at 0.5 m x 0.5 m, corresponding with a net plot of 41 x 41 grid points; coarser grids produced inaccurate results, finer grids took too much computer time.

* LOTUS 1-2-3 Release 2 (1985) and SURFER Access System Version 4.06 (1984) are registered trademarks of the Lotus Development Corporation and the Golden Software Inc., respectively.

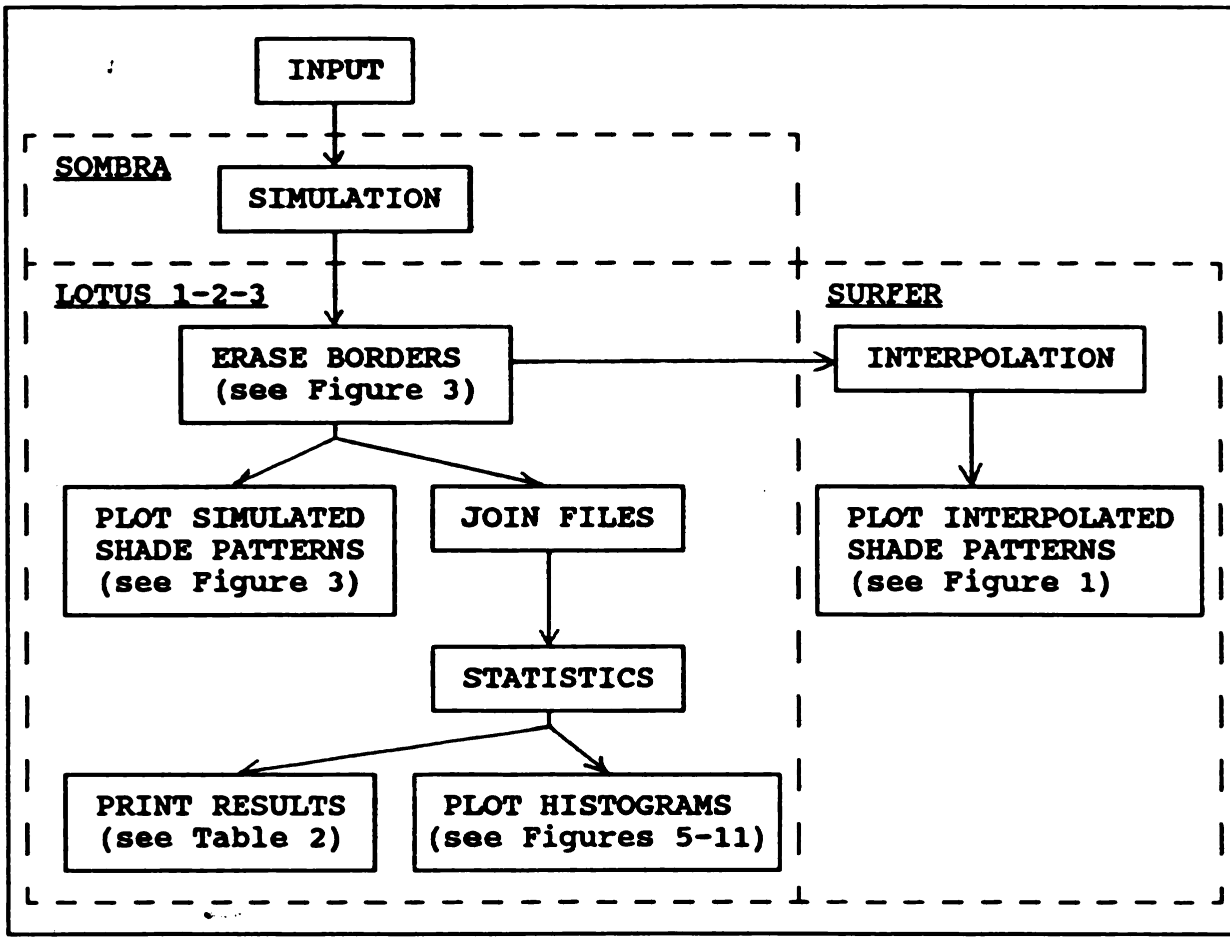


Figure 2. Flow chart of the analysis of shade patterns.

Based on field observations in the Atlantic Zone a "standard" tree was defined with a stem of 6 m height and a hemi-spherical crown of 4 m height and 8 m in diameter (Figure 3). These were spaced at 10 m x 10 m; with the sun right above the plot 47 % of the area was covered by shade (Figure 4).

The shade pattern was simulated between 8.30 am and 15.30 pm (at 9, 10, 11, 12, 13, 14, 15 o'clock; 7 hours). During these hours the impact of sunshine is strongest (although early morning sunshine may be important to evaporate water films formed on leaves and fruits during the night, which favour the germination of spores). Simulation of shade patterns during early morning or late afternoon hours would require wider borders and more computation time.

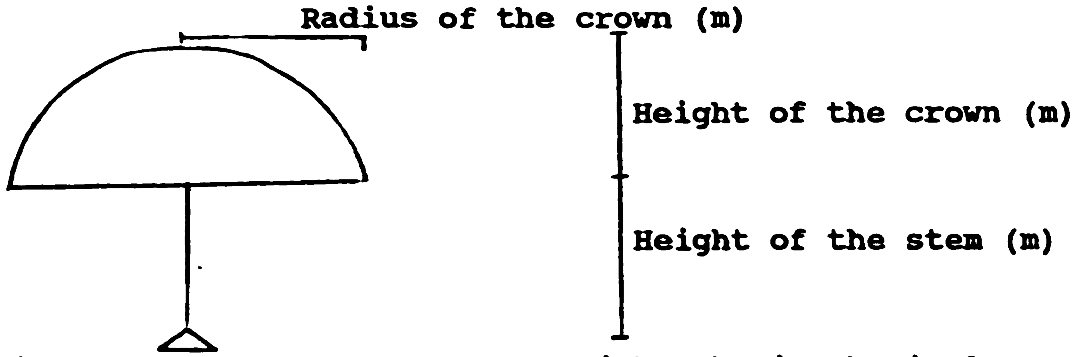


Figure 3. The "standard" tree with a hemi-spherical crown. (m)

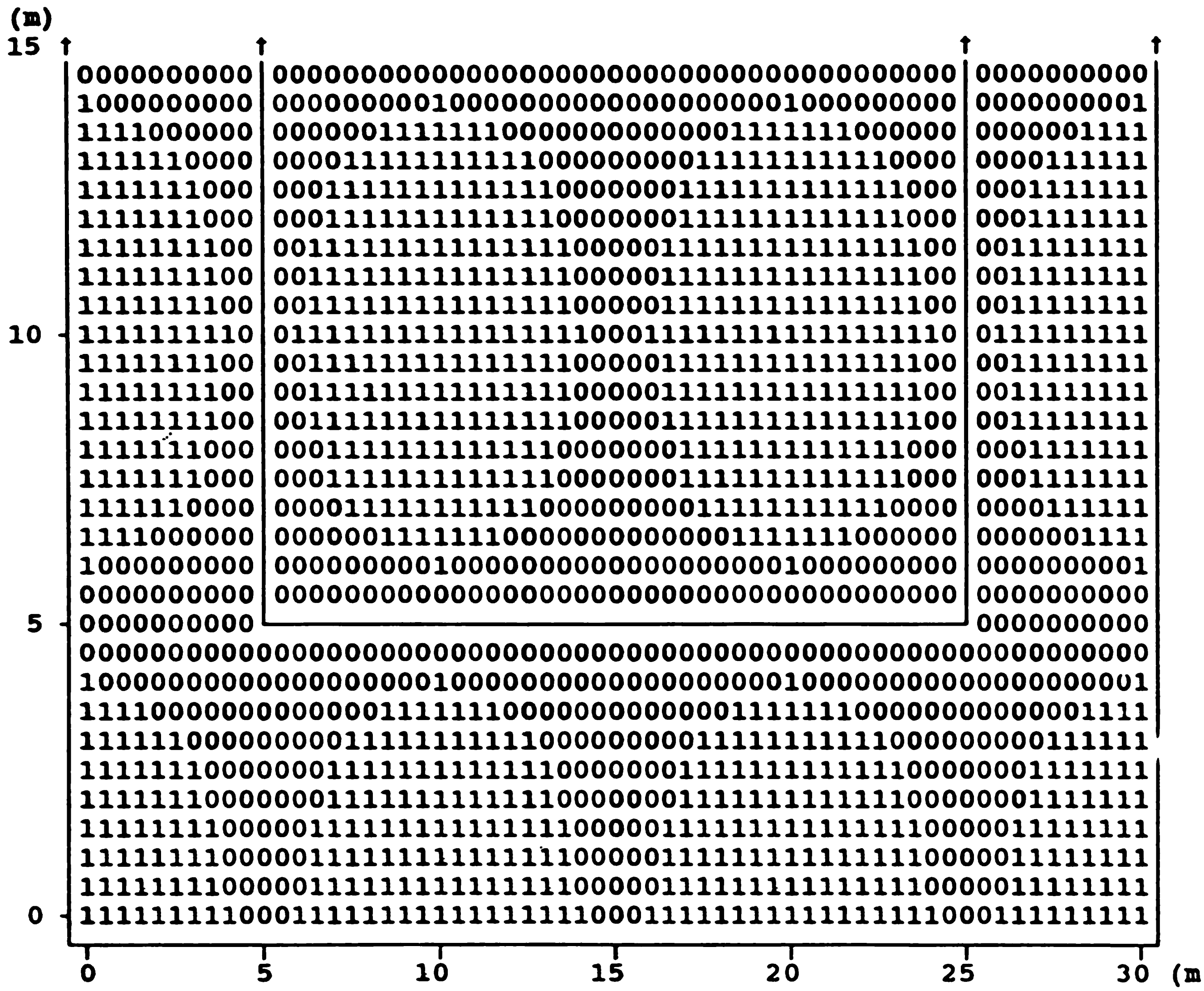


Figure 4. Gross and net plot as "observed" by the simulation programme when the sun is right above it; 0 = sun, 1 = shade. Points on the limits of the net plot are included in the calculations. For reasons of space only half of the plot can be shown here.

3.2 Choice of comparisons

Assuming that the amount and distribution of shade change with the conditions of the plot (latitude, season, slope) and the characteristics of the shade trees (plant arrangement, height of stem and crown) several "treatments" were chosen (Table 1). The latitude, season and slope determine the angle between incoming sunrays and the plot. The farmer cannot change them, but by selecting the species (form) of shade trees, planting them in certain arrangements and pruning them, he can optimize the amount and distribution of shade for any of these "fixed" conditions.

The second treatment of Table 1 may be considered as "standard" for Costa Rica conditions; all other treatments differ in only one factor. The comparisons within each column are underlined.

Table 1. Overview of the different treatments and comparisons.

	Latitude (°N)	Season (month)	Slope of plot (°)	Shade tree arrangement	Height of stem (m)	Height of crown (m)
1	<u>0</u>	March	0	Square	6	4
2	<u>10</u>	<u>March</u>	<u>0</u>	<u>Square</u>	<u>6</u>	<u>4</u>
3	<u>20</u>	March	0	Square	6	4
4	10	<u>August</u>	0	Square	6	4
5	10	<u>December</u>	0	Square	6	4
6	10	March	<u>45</u>	Square	6	4
7	10	March	0	<u>Triangular</u>	6	4
8	10	March	0	<u>E-W rows</u>	6	4
9	10	March	0	<u>N-S rows</u>	6	4
10	10	March	0	Square	<u>12</u>	4
11	10	March	0	Square	6	<u>8</u>

Latitude (°N) of the plot

The choice of latitudes was based on the fact that 0° is the centre of the cocoa belt (75 % of the world's cocoa is grown between 8° South and 8° North), 10° is the latitude of Costa Rica and 20° is the ecological limit for cocoa growing.

Seasonality of the sunshine

The angle between the rays of the sun and the surface of the plot changes with the seasons. Shade patterns in Costa Rica (10 °N) were simulated for March, August and December.

Slope of the plot

Cocoa is often grown on slopes. Shade patterns of a flat plot and a plot on a very steep 45° slope facing the south were compared.

Arrangement of the shade trees

Shade trees usually are planted in rows with equal spacing within and between rows, about 9-12 m. The standard chosen was a square plant arrangement of 10 m x 10 m, with rows running N-S (or E-W). The "triangular" plant arrangement was simulated by shifting the direction of these rows to NE-SW (or SE-NW). The other treatments were rows running N-S and E-W, respectively, with 16.7 m between rows and 6.0 m within rows. All treatments had the same number of trees per ha and the same vertical projection of their crown area (on a horizontal plane: 47 %).

Form of the shade trees

In most comparisons the standard tree was used: a stem of 6 m and a hemi-spherical crown with a radius (and height) of 4 m. In one of the treatments the height of the stem was increased to 12 m and in another the height of the crown was doubled, resulting in a hemi-elliptical shape. All crowns had the same vertical projection (47 % of the area of the plot).

4 RESULTS AND DISCUSSION

4.1 Summary of the results

Table 2 gives an overview of the results. In the next paragraph the results will be presented graphically and discussed in more detail. Here only some explanations are given.

The treatment underlined in Table 2 forms part of most comparisons. It simulates shade in March, on a plot without slope, with a spacing of 10 m x 10 m (N-S/E-W square) of standard trees (stem 6 m, crown 4 m). The results are presented in Figure 5.

Table 2. Summary of the results of the simulations.

	Latitude °N			Month		Slope	Tree arrangement			Stem	Crown
	0°	10°	20°	Aug	Dec	45°	Δ	N-S	E-W	12 m	8 m
Hours of shade (h)											
Mean including 0's	1.9	1.9	1.7	3.7	4.5	1.2	1.7	2.2	2.7	1.9	1.6
Mean excluding 0's	4.9	4.7	4.9	4.8	4.7	5.9	4.6	3.2	6.2	4.7	5.3
S.D. including 0's	2.4	2.4	2.2	2.4	1.7	0.9	2.0	0.8	3.2	2.3	2.4
S.D. excluding 0's	1.3	1.6	1.4	1.5	1.5	0.9	1.5	0.87	1.4	1.4	1.5
Points x hours shade (%)	53	53	58	53	64	85	59	46	37	53	62
Without shade (% points)	24	22	17	22	4	0	10	0	59	20	18
Little shade (% points)	5	10	5	8	12	0	10	17	1	5	6
1 hour	2	4	2	3	3	0	3	0	0	2	1
2 hours	3	6	3	5	9	0	7	17	1	3	5
Moderate shade (% points)	40	38	45	41	49	24	48	83	8	48	30
3 hours	7	7	8	7	9	1	9	49	4	11	6
4 hours	12	11	13	13	14	7	16	31	2	21	10
5 hours	22	20	24	22	27	17	23	3	2	16	15
Much shade (% points)	31	30	33	29	34	76	32	0	32	27	46
6 hours	27	25	27	23	29	50	30	0	2	20	31
7 hours	4	5	6	6	5	25	2	0	30	6	15
Total shade (% points)	76	78	83	78	96	100	90	100	41	80	82

Means and standard deviations (S.D.) were calculated in two ways: including and excluding, respectively, the points which did not receive any shade at all. One may imagine a plot with many points without shade, which would result in a high overall standard deviation, but with shade evenly distributed over the points that do receive shade, giving a small standard deviation between these points.

The maximum quantity of shade that can be received by the net plots defined in paragraph 3.1 is 41 x 41 x 7 = 11767 points x hours. The maximum number of points with shade is 41 x 41 = 1681 points.

The classsification of the hours of shade in three groups was done intuitively, as no information was available about the relation between hours of shade and the performance of the cocoa crop.

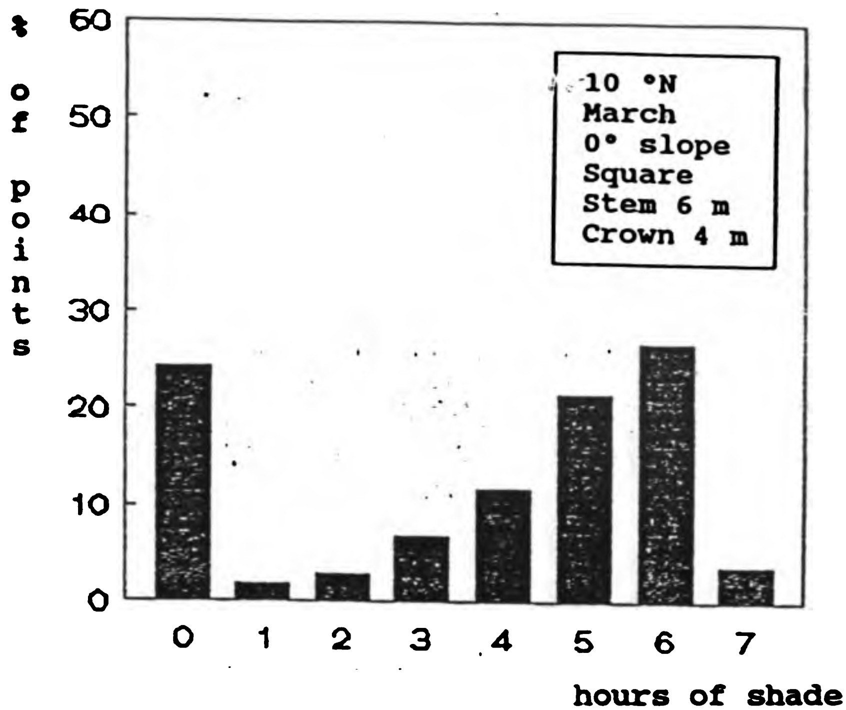


Figure 5. The distribution of shade in the "standard" plot.

4.2 Latitude of the plot

The differences caused by the latitude were rather small (Figures 5 and 6): at 20 °N fewer points received no shade at all, more points fell into the group of moderate shade and the % of points x hours with shade was higher. The situation changes with the seasons. Probably the largest difference will be found between 20 °N and 20 °S, in June and December.

4.3 Seasonality of the sunshine

For plots at 10 °N (Costa Rica) the differences between March and August were small. In December very few points received no shade and there were more points with moderate or much shade. This means that the same shade trees - apart from the possibility of shedding their leaves - give different amounts and distributions of shade during the year (Figures 5 and 7).

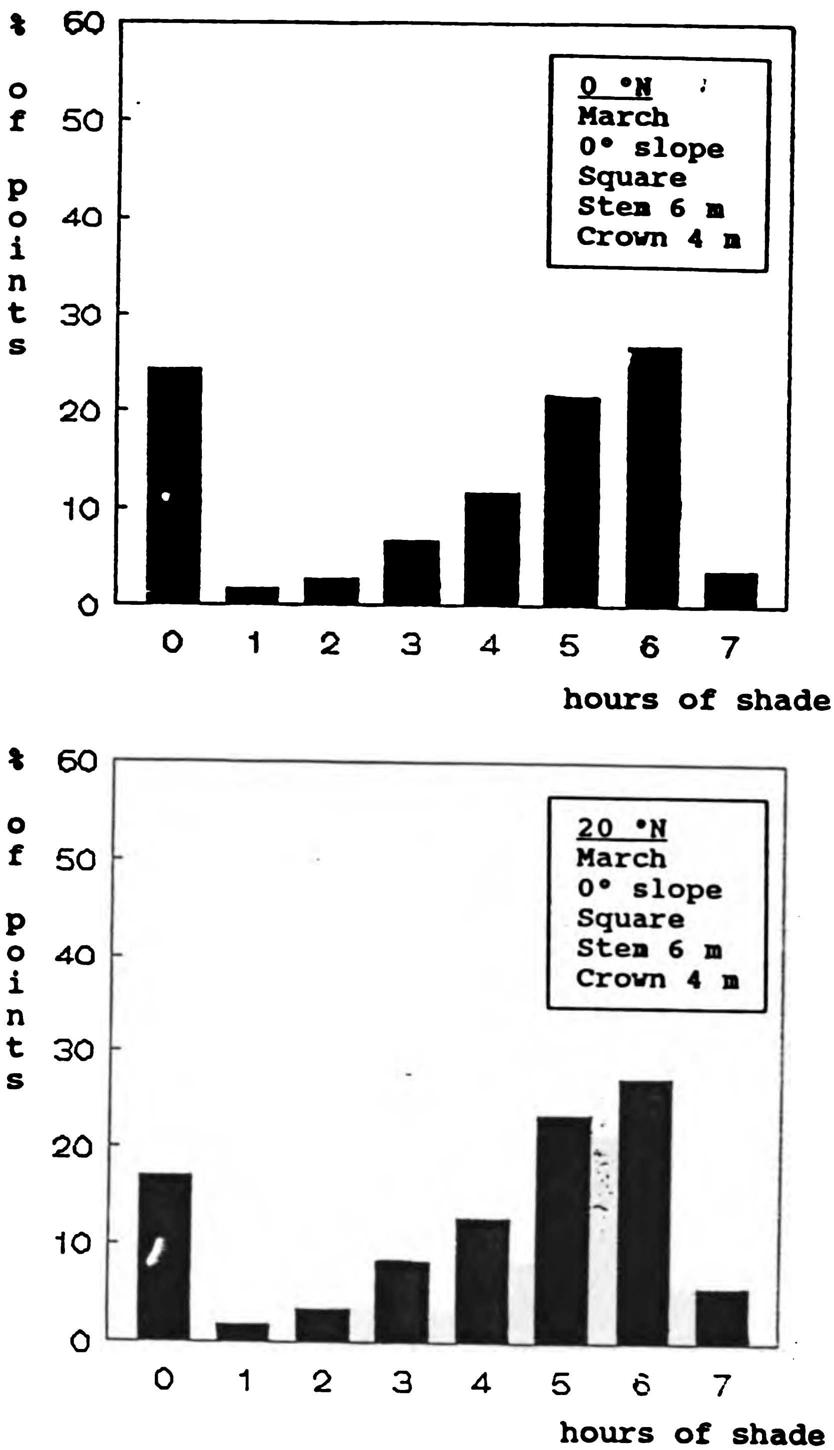


Figure 6. The distribution of shade at 0 °N and 20 °N (compare with Figure 5).

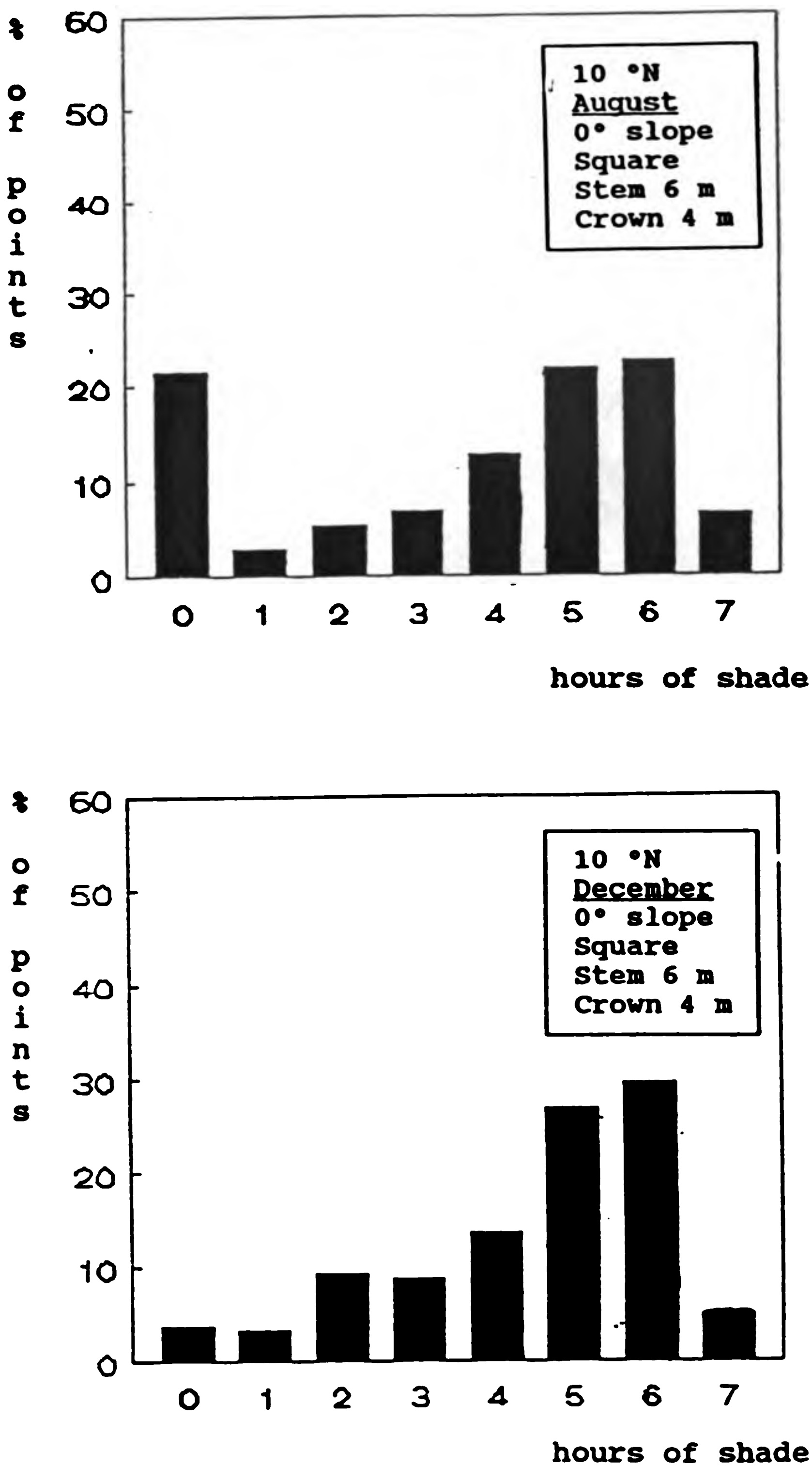


Figure 7. The distribution of shade in August and December (compare with Figure 5).

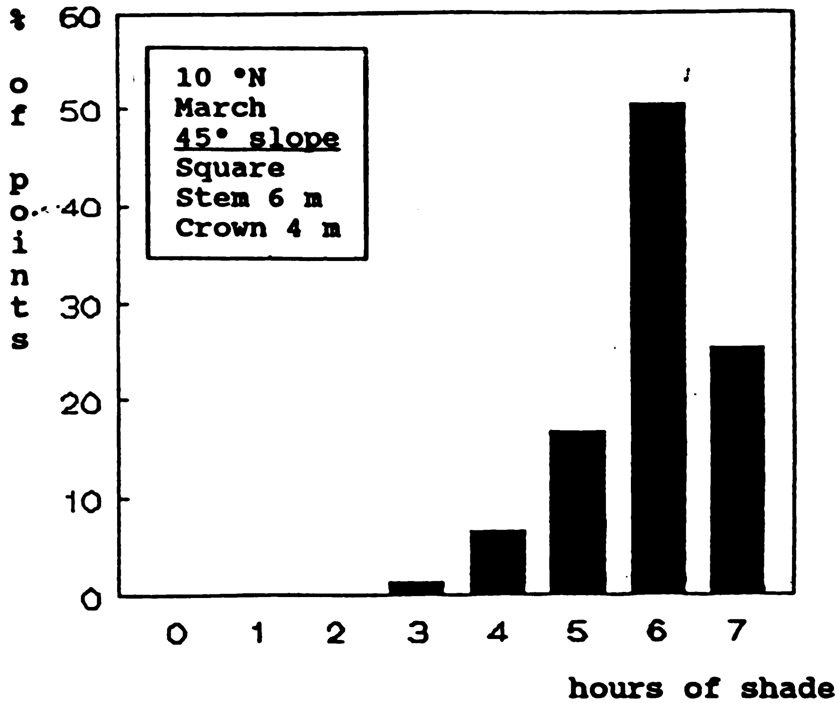


Figure 8. The distribution of shade on a southern slope of 45° (compare with Figure 5).

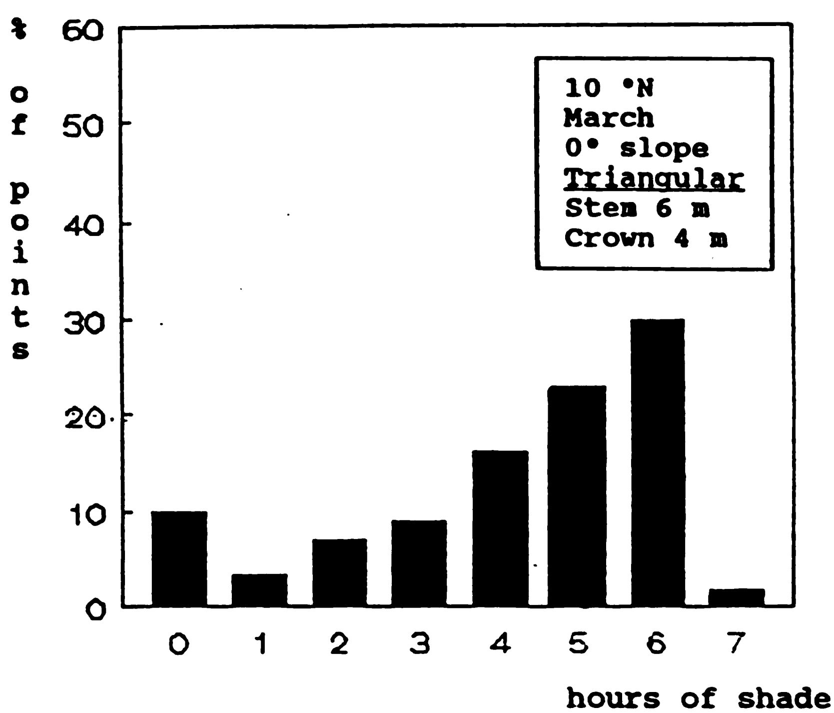
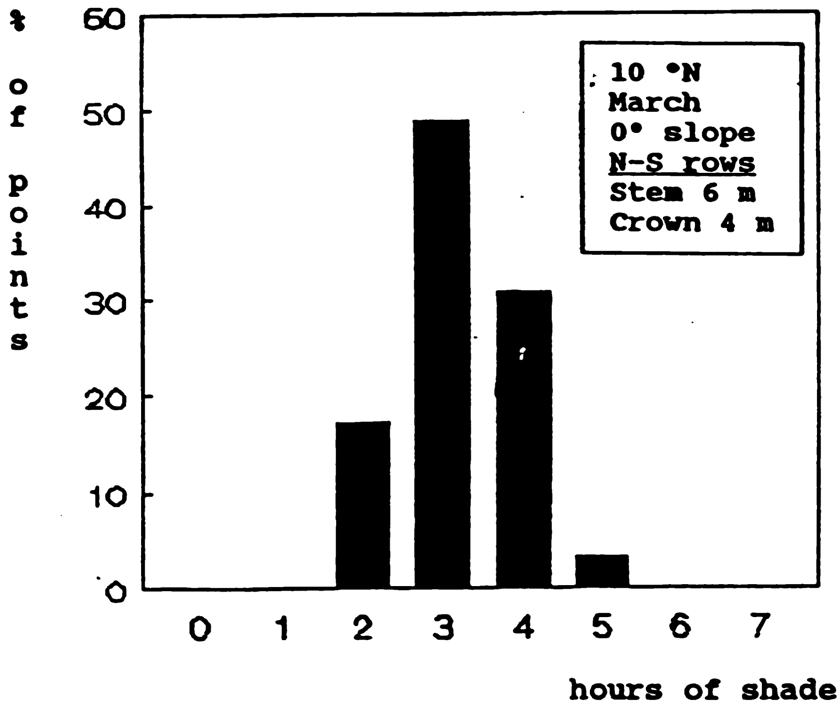


Figure 9. The distribution of shade with shade trees planted in a triangular pattern (compare with Figure 5).



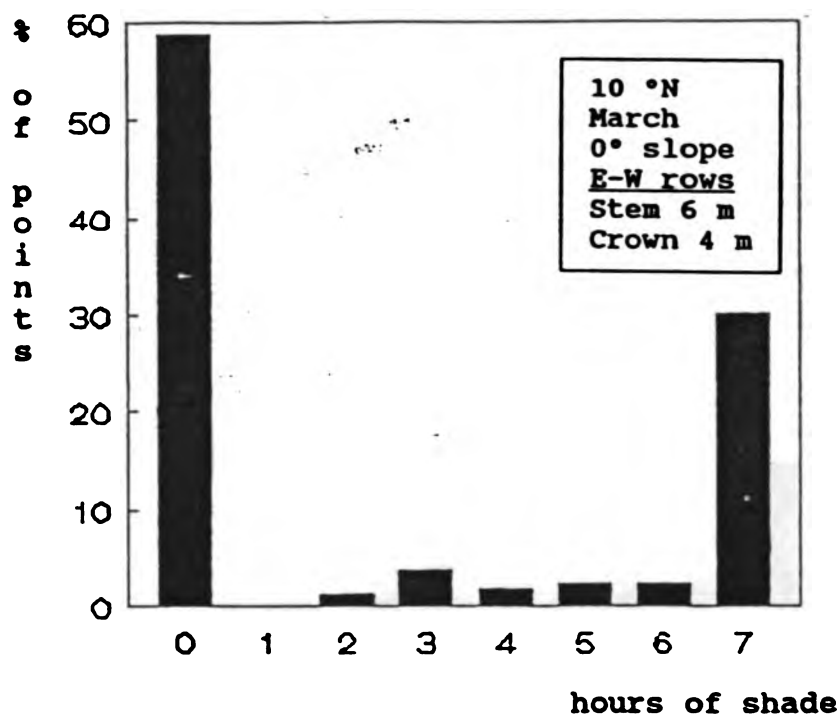


Figure 10. The distribution of shade with the shade trees planted in N-S or E-W rows (compare with Figure 5).

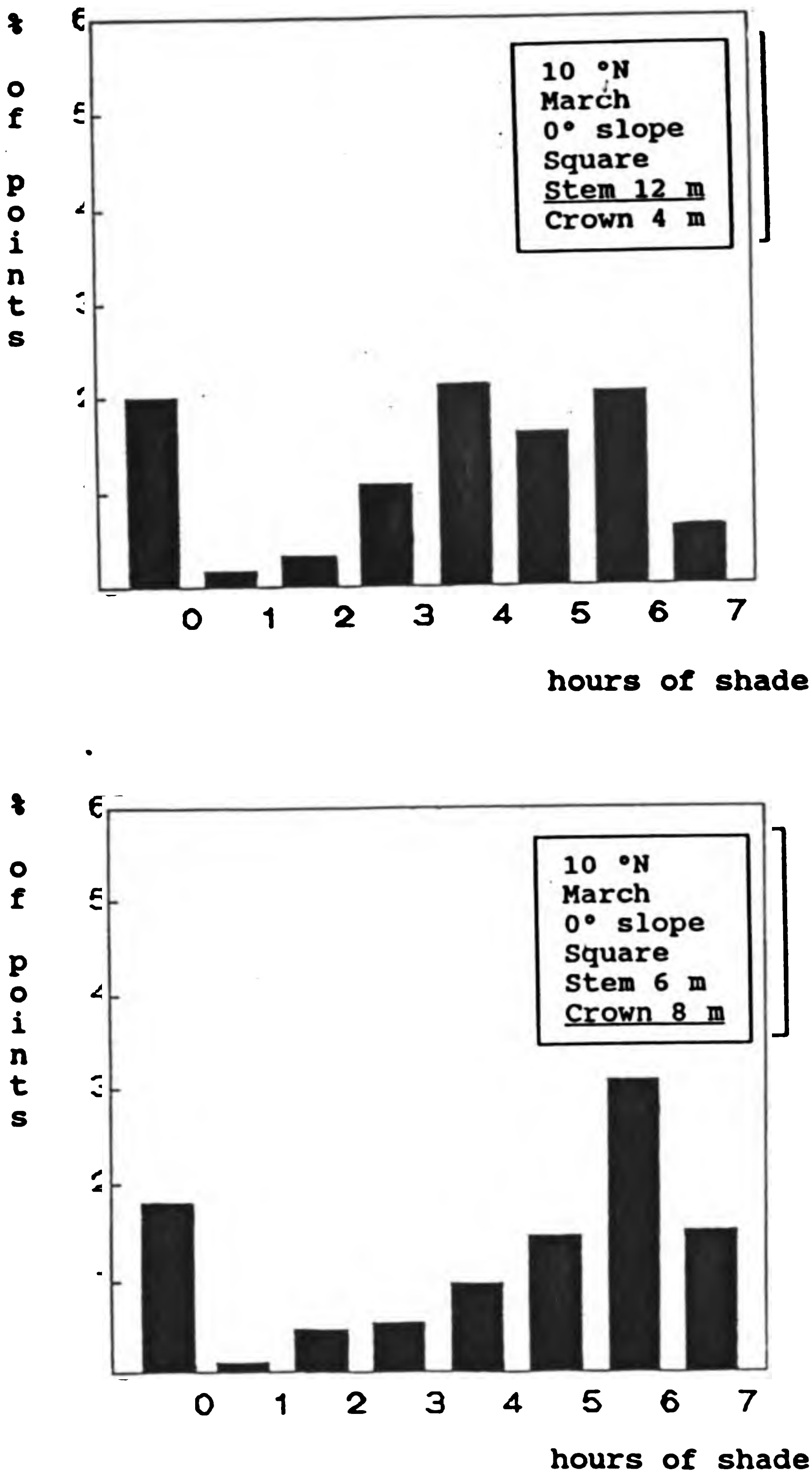


Figure 11. The distribution of shade as a function of the form of the shade trees (height of stem and crown) (compare with Figure 5).

4.4 Slope of the plot

The slope of the plot had a very strong influence on the amount and distribution of shade (compare figures 5 and 8). All points of the plot on the southward facing slope received moderate to much shade; this means that fewer shade trees need to be planted. The effect of slopes might be studied in more detail by comparing slopes with different directions at different latitudes and in different seasons.

4.5 Arrangement of the shade trees

Surprisingly, most literature recommends to plant shade trees in square arrangements of 9 m x 9 m, 10 m x 10 m or 12 m x 12 m, which combine well with cocoa planted at 2.5 m x 2.5 m or at 3 m x 3 m. However, the simulations showed that the distribution of shade was more even when the shade trees were planted in a triangular pattern and very even when they were planted in N-S rows (Figures 5, 9, 10). Rows running E-W gave a very uneven distribution of shade, with most points receiving either none or very much shade (better for intercropping with a sun-loving crop than for shading cocoa).

The results correspond well with MUTSAERS' (1980) study of the light absorption by hedgerows. It might prove interesting to repeat the simulations with different spacings between and within the rows.

4.6 Form of the shade trees

The form of the shade trees had a strong influence on the amount and distribution of shade (Figures 5 and 10). Taller crowns with the same radius and stem gave more shade, with an uneven distribution. Taller stems with the same crowns did not change the amount of shade, but improved the distribution.

4.7 Limitations of the study

Although the work presented gives a clear indication of the potential of the simulation of shade patterns, there are several limitations. Some are inherent to the simulation programme, others are due to the ways in which it was used.

Sunshine and solar energy

The simulation took place from 8.30 am to 15.30 pm; earlier or later sunshine was neglected. The programme assumes sunshine all over the day, which often is not correct. This is not just a matter of more or less hours of shade, but may bias comparisons. In the tropics, for example, rain often falls in the afternoon, which means that slopes facing the west receive less hours of sunshine than those facing the east (WIENK, 1986). To improve the analysis data from Campbell-Stokes recorders should be used.

Sunshine is clearly not the same as solar energy, which differs from country to country, from month to month, and from hour to hour. This means that one hour of light or shade, depending on the when and where, may have a very different effect on cocoa growth and development. Moreover the programme neglects the importance of diffuse light.

Characteristics of shade trees

The programme does not allow for the transmission and reflection of light by the crowns of the trees, which are supposed to be opaque. Moreover the seasonal loss of leaves by (semi-)deciduous trees should be taken into account.

In this study only one type of tree per plot was simulated, while farmers often use a mixture of shade trees, especially where tree crops were planted under the shade of left over forest trees. The programme can simulate mixtures of very different sizes and forms of trees, although the collection of data in farmers' fields and their entry in the model can be quite time consuming.

Interactions and combinations

In this study only one variable was studied each time. However, as shown, in practice there are strong interactions between factors. Before making recommendations for specific conditions the different combinations of variables should be studied with care. An unexplored advantage of the programme is the possibility to study shade patterns at different height levels, by increasing or reducing the height of the stems of the trees. In the present study shade was "measured" at ground level, but the model may easily be adapted to shaded or mixed crops of different heights.

5 CONCLUSIONS

There is little information on the optimal plant arrangements, sizes and shapes of shade trees for different conditions. The present study used a simulation programme to study factors related with the choice and management of shade trees.

The effects of latitude and season are limited by the fact that cocoa is grown between 20 °S and 20 °N. In spite of that, some combinations of latitude and season give clear differences in the amount and distribution of shade.

The effect of slopes can be very strong; the interaction between the direction and inclination of slopes and latitude and season should be studied in more detail.

The plant arrangement of shade trees - a factor which farmers can manipulate easily on cleared land - had a very strong influence on the amount and distribution of shade. It is surprising that most literature recommends square shade tree arrangements.

Trees with tall stems give less and better distributed shade than those with heigh crowns, other dimensions being equal.

In spite of some limitations the simulation programme developed by CATIE is a very useful tool for the analysis of light and shade patterns in crops grown under shade or in multiple cropping systems.

6 REFERENCES

BEER, J., 1987. Advantages, disadvantages and desirable characteristics of shade trees for coffee, cacao and tea. Agroforestry Systems 5: 3-13.

BUY F. du & W. van KOUWEN, 1991. El cultivo del cacao en la Zona Atlántica de Costa Rica; un análisis preliminar del crecimiento de cacao híbrido. Working Documents No. 11. Atlantica Zone Programme (CATIE/UAW/MAG). CATIE. Turrialba, Costa Rica.

CUNNINGHAM, R.K. & J.C. BURRIDGE, 1960. The growth of cacao (*Theobroma cacao*) with and without shade. Annual Botany 24: 458-462.

DIAZ, M.J., 1957. Algunas observaciones sobre la incidencia de Monilia del cacao en el Ecuador. Revista Turrialba (Costa Rica) 7: 95-99.

ENRIQUEZ, G.A., 1985. Curso sobre el cultivo del cacao. CATIE. Turrialba, Costa Rica.

ENRIQUEZ, G. & A. PAREDES, 1985. El cultivo del cacao. Editorial Universidad Estatal a Distancia (EUNED). San José, Costa Rica.

EVANS, H & D.B. MURRAY, 1953. A shade and fertilizer experiment on young cacao. Report on cocoa research 1945-1951. Trinidad.

GALINDO, J.J. & G.A. ENRIQUEZ, 1984. Estrategias para el combate de la moniliasis del cacao. CATIE. Turrialba, Costa Rica.

HOLDRIDGE, L.R & L.J. POVEDA, 1975. Arboles de Costa Rica. Volumen 1. Centro Cientifico Tropical. San José, Costa Rica.

JIMENEZ, G., 1980. El sombreamiento del cacao. CATIE. Turrialba, Costa Rica.

KAY, D., 1961. Dieback of cocoa. Technical Bulletin No. 196. West African Cocoa Research Institute. Ibadan, Nigeria.

LASS, R.A., 1986. Diseases. In: G.A.R. Wood and R.A. Lass (eds.), 1986. Cocoa. Longman Scientific and Technical. Essex, England.

MARTINEZ, A. & G. ENRIQUEZ, 1984. La sombra para el cacao. CATIE. Turrialba, Costa Rica.

MUTSAERS, H.J.W., 1980. The effect of row orientation, date and latitude on light absorption by row crops. Journal of Agricultural Science (Cambridge) 95: 381-386.

NAIR , P.K.R., 1979. Intensive multiple cropping with coconuts in India: principles, programmes and prospects. Parey. Berlin, Germany.

PURSEGLOVE, J.W., 1987. Tropical crops: Dicotyledons. Longman Scientific and Technical. Essex, England.

QUESADA, F. & E. SOMARRIBA & E. VARGAS, 1987. Modelo para la simulación de patrones de sombra de árboles. CATIE. Turrialba, Costa Rica.

SANCHEZ, 1983. Flórula del Parque Nacional Cahuita. Editorial Universidad Estatal a Distancia (EUNED). San José, Costa Rica.

SOMARRIBA, J. & J.W. BEER, 1987. Dimensions, volumes and growth of Cordia alliodora in agroforestry systems. Forest Ecology and Management 18: 113-126.

WAAIJENBERG, H. & M. WESSEL, 1989. Proposals for research on cocoa and tuber crops. Atlantic Zone Programme. Guápiles, Costa Rica. (unpublished)

WAAIJENBERG, H. & C.J. TAZELAAR, 1990. La problemática del cacao en la Zona Atlántica de Costa Rica. Presentación en el "Taller Información de Suelos", Guápiles, Costa Rica, 2-4 octubre 1990.

WESSEL, M., 1986. Shade and nutrition. In: G.A.R. WOOD & R.A. LASS (eds.), 1986. Cocoa. Longman Scientific and Technical. Essex, England.

WIENK, J.F., 1986. Ecologie, teelttechniek en gewas. Collegedictaat LUW. Landbouwuniversiteit. Wageningen, The Netherlands.

WOOD, G.A.R., 1986. Environment and establishment. In: G.A.R. WOOD & R.A. LASS (eds.), 1986. Cocoa. Longman Scientific and Technical. Essex, England.

APPENDIX 1. NAMES OF SHADE TREES

1	Anonillo	*Annona* sp.
2	Aguacate	*Persea americana*
3	Balsa	*Ochroma lagopus*
4	Banano	*Musa* AAA
5	Banano criollo	*Musa* AAA
6	Cacao viejo	*Theobroma cacao*
7	Carambola	*Averrhoa carambola*
8	Cedro	*Cedrela mexicana*
9	Cocotero	*Cocos nucifera*
10	Crotón	*Codiaeum variegatum*
11	Gavilán	*Pentaclethra macroloba*
12	Guanacaste	*Enterolobium cyclocarpum*
13	Guavo (Guabo)	*Inga* spp.
14	Guanabana	*Annona muricata*
15	Hiquerilla	*Ricinus communis*
16	Hule silvestre	*Castilla elastica*
17	Indio desnudo	*Bursera simaruba*
18	Javillo (Jabillo)	*Hura crepitans*
19	Lagartillo	*Zanthoxylum insulare*
20	Laurel	*Cordia alliodora*
21	Limón ácido	*Citrus aurantifolia*
22	Madero negro	*Gliricidia sepium*
23	Mango	*Mangifera indica*
24	Manzana de aqua	*Eugenia malaccensis*
25	Manzana rosa	*Eugenia jambos*
26	Melina	*Gmelina arborea*
27	Nuez muscada	*Myristica fragans*
28	Naranja	*Citrus sinensis*
29	Níspero	*Manilkara achras*
30	Palma africana	*Elaeis guineensis*
31	Pejibaye	*Bactris gasipaes*
32	Platano	*Musa* AAB
33	Poró	*Erythrina* spp.
34	Poró gigante	*Erythrina poeppigiana*
35	Tamarindo	*Tamarindus indica*
36	Teca	*Tectona grandis*
37	Toronja	*Citrus* spp.
38	Yuca	*Manihot esculenta*
39	Yumplón	*Spondias dulcis*
40	Zapote	*Calocarpum mammosum*
41	Unknown	

APPENDIX 2. DISTRIBUTION OF SHADE TREES

The following shade trees were observed in an area of 500-1000 m² per farmer in the cantons Guácimo (1-10) and Talamanca (11-20).

Name of tree	Farmer	# of trees
Total		580
1 Anonillo		1
	20	1
2 Aguacate		20
	2	4
	5	5
	7	2
	8	2
	14	4
	17	3
3 Balsa		11
	2	1
	11	1
	13	5
	15	2
	16	1
	20	1
6 Cacao viejo		33
	16	16
	19	17
7 Carambola		1
	8	1
8 Cedro		40
	3	3
	4	4
	6	3
	7	20
	8	2
	9	1
	12	1
	15	4
	17	2

Name of tree	Farmer	# of trees
9 Cocotero		24
	1	2
	5	16
	8	2
	10	2
	14	1
	17	1
10 Crotón		10
	2	2
	6	8
11 Gavilán		3
	15	1
	18	2
12 Guanacaste		2
	18	2
13 Guavo		71
	1	2
	2	19
	3	5
	4	3
	6	5
	8	1
	9	5
	11	5
	13	2
	16	3
	17	2
	18	12
	19	6
	20	1
14 Guanábana		2
	2	1
	14	1
15 Higuerilla		11
	12	1
	13	1
	15	9

Name of tree	Farmer	# of trees
16 Hule silvestre		9
	6	1
	8	2
	9	1
	13	1
	16	3
	17	1
17 Indio desnudo		6
	4	3
	9	1
	15	1
	16	1
18 Javillo		14
	3	1
	4	4
	9	9
19 Lagartillo		1
	11	1
20 Laurel		97
	4	3
	6	1
	7	5
	8	3
	9	1
	11	1
	14	35
	15	1
	16	1
	17	8
	18	2
	19	7
	20	29
21 Limón ácido		1
	8	1
22 Madero negro		26
	7	9
	10	7
	12	10
23 Mango		1
	4	1

Name of tree	Farmer	# of trees
24 Manzana de agua		1
	20	1
25 Manzana rosa		3
	11	2
	17	1
26 Melina		13
	11	2
	15	6
	17	5
27 Moscadero		4
	14	1
	19	3
28 Naranja		10
	2	1
	4	8
	8	1
30 Palma africana		2
	3	1
	15	1
31 Pejibaye		7
	4	1
	5	1
	8	1
	13	1
	16	1
	17	1
	18	1
33 Poró		34
	1	7
	6	1
	7	2
	10	14
	11	7
	12	1
	18	2
34 Poró gigante		6
	5	4
	10	1
	18	1

Name of tree	Farmer	# of trees	Name of tree	Farmer	# of trees
35 Tamarindo		1	44 Musa spp.		68
	18	1		5	1
				8	6
36 Teca		2		12	8
	15	2		13	33
				14	1
38 Yuca		6		16	6
	14	6		17	1
				19	12
39 Yumplon		1			
	3	1			
40 Zapote		3			
	7	3			
41 Unknown		35			
	3	1			
	4	9			
	6	3			
	10	5			
	11	1			
	13	2			
	15	2			
	16	1			
	17	8			
	18	3			

APPENDIX 3. CROWNS OF SHADE TREES

The 580 shade trees measured in farmers' fields had the following types of crowns (see QUESADA et al., 1987). The dimensions per species are given in Appendix 4.

Hemi-spherical	204	trees
Inversed conical	133	"
Hemi-elliptical	128	"
Elliptical (vertical)	79	"
Spherical	15	"
Conical	14	"
Elliptical (horizontal)	7	"
Total	580	"

APPENDIX 4. DIMENSIONS OF SHADE TREES

Height of the stem (m)

	Mean	Standard Deviation	# of trees
All trees	6.9	6.5	580
Anonillo	23.3	0.0	1
Aguacate	3.9	2.0	20
Balsa	8.1	5.2	11
Banano	3.0	0.8	13
Banano criollo	3.7	1.1	6
Cacao viejo	2.9	0.9	33
Carambola	1.0	0.0	1
Cedro	9.1	4.8	40
Cocotero	4.5	1.6	24
Crotón	4.5	2.0	10
Gavilán	8.9	5.6	3
Guanacaste	24.1	0.0	2
Guavo	7.2	4.6	71
Guanábana	3.5	1.1	2
Hiquerilla	3.9	0.6	11
Hule silvestre	10.2	8.0	9
Indio desnudo	6.7	2.4	6
Javillo	8.0	3.0	14
Lagartillo	15.5	0.0	1
Laurel	12.6	10.9	97
Limón ácido	2.0	0.0	1
Madero negro	4.9	1.5	26
Mango	2.5	0.0	1
Manzana de agua	7.6	0.0	1
Manzana rosa	1.3	0.2	3
Melina	3.4	1.0	13
Moscadero	1.2	0.5	4
Naranja	2.9	0.8	10
Palma africana	5.7	6.0	2
Pejibaye	5.5	1.3	7
Plátano	3.2	0.8	49
Poró	5.1	3.2	34
Poró gigante	5.8	3.5	6
Tamarindo	8.8	0.0	1
Teca	6.1	4.5	2
Yuca	2.0	0.0	6
Yumplon	6.2	0.0	1
Zapote	5.9	1.4	3
Unknown	10.2	6.5	35

Height of the crown (m)

	Mean	Standard Deviation	# of trees
All trees	7.3	6.2	580
Anonillo	30.1	0.0	1
Aguacate	5.5	2.8	20
Balsa	6.8	6.1	11
Cacao viejo	2.2	0.7	33
Carambola	8.7	0.0	1
Cedro	9.9	7.3	40
Coco	7.2	2.6	24
Croto	4.3	1.1	10
Gavilan	10.3	5.4	3
Guanacaste	29.3	0.0	2
Guavo	8.1	5.7	71
Guanabana	4.0	4.6	2
Hiquerilla	4.7	0.7	11
Hule silvestre	16.5	8.2	9
Indio desnudo	6.5	4.1	6
Javillo	10.3	5.1	14
Lagartillo	18.0	0.0	1
Laurel	9.3	0.8	97
Limón ácido	2.4	0.0	1
Madero negro	6.7	5.1	26
Mango	7.5	0.0	1
Manzana de agua	10.7	0.0	1
Manzana rosa	2.2	0.2	3
Melina	4.6	2.0	13
Moscadero	7.1	3.6	4
Naranja	4.5	1.6	10
Palma africana	8.5	2.2	2
Pejibaye	6.9	4.1	7
Poró	5.8	4.5	34
Poró gigante	14.2	9.4	6
Tamarindo	7.2	0.0	1
Teca	5.6	3.9	2
Yuca	1.6	0.0	6
Yumplon	9.7	0.0	1
Zapote	7.4	7.4	3
Unknown	12.1	8.9	35
Musa spp.	2.3	1.8	68

Radius of the crown (m)

	Mean	Standard Deviation	# of trees
All trees	4.2	2.2	580
Anonillo	6.0	0.0	1
Aguacate	3.8	4.0	20
Balsa	4.5	1.8	11
Banano	3.1	0.8	13
Banano criollo	3.0	0.0	6
Cacao viejo	3.6	0.7	33
Carambola	5.0	0.0	1
Cedro	4.8	2.2	40
Cocotero	5.0	1.4	24
Crotón	3.9	1.3	10
Gavilán	6.3	1.5	3
Guanacaste	11.0	0.0	2
Guavo	6.2	2.0	71
Guanábana	4.5	3.5	2
Higuerilla	3.2	0.4	11
Hule silvestre	6.6	3.1	9
Indio desnudo	3.8	0.9	6
Javillo	6.2	3.2	14
Lagartillo	3.0	0.0	1
Laurel	3.1	1.4	97
Limón ácido	2.0	0.0	1
Madero negro	4.7	1.5	26
Mango	3.0	0.0	1
Manzana de agua	5.0	0.0	1
Manzana rosa	1.6	0.5	3
Melina	2.8	0.8	13
Moscadero	1.2	0.5	4
Naranja	2.9	1.1	10
Palma africana	5.5	4.9	2
Pejibaye	3.2	1.3	7
Plátano	2.1	0.7	49
Poró	4.9	1.9	34
Poró gigante	5.1	1.6	6
Tamarindo	4.0	0.0	1
Teca	3.5	0.7	2
Yuca	1.0	0.0	6
Yumplon	4.0	0.0	1
Zapote	4.3	1.1	3
Unknown	5.6	2.0	35