

## CALCULATED YIELD TRENDS OF COCOA IN DIFFERENT COUNTRIES

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### INTRODUCTION

The explanation of the biological processes underlying growth and yield formation in cocoa crops is one of objectives of physiologists. Agronomists would be able to evaluate the consequence of specific husbandry decisions beforehand, and breeders would gain in efficiency when they are able to define crop characteristics of a desirable cocoa ideotype. Anten *et al.* (1993) showed that the modelling approach was a valuable tool to quantify and test our hypotheses concerning the growth and production of cocoa. They developed a quantitative model on the basis of the conceptual ideas of Hutcheon (1976a,b). Other quantitative models developed for the physiology of cocoa were constructed by Borchert (1973) and Ng (1982). None of these models have been used to study the growth and production of cocoa for extended periods.

The model of Anten *et al.* (1993) was extended with the aim of studying the influence of weather and soils on growth and production of cacao in three different environments over periods of at least ten years. Subsequently, a water balance was introduced and limitations due to water stress on the cocoa were accounted for.

### MODEL DESCRIPTION

The models Cacao Simulation Environment (CASE) 1 and 2 for potential and water limited production circumstances respectively are based on the SUCROS87 and SUCROS2 models described by Spitters *et al.* (1989) and van Laar *et al.* (1992). The models are formulated in

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FORTRAN77 and make use of the simulation libraries developed at the Centre for Agrobiological Research in Wageningen. In Figure 1 the most important steps are presented in a conceptual model for plant production at the potential level (CASE1). The calculation of crop growth starts with light interception by the cocoa canopy. This depends on the shade regime, Leaf Area Index (LAI) and the extinction coefficient of the cocoa crop. The intercepted light drives the leaf  $\text{CO}_2$  assimilation process. Leaf  $\text{CO}_2$  assimilation is integrated over the total crop LAI. The produced sugars are used to maintain the standing biomass in the first place, a process called maintenance respiration. The remaining sugars are termed reserves. Only a part of the reserve sugars is used for growth of structural dry matter of the plant organs. In the model track is kept of structural dry matter pools for roots, trunk, leaves and pods. The transformation of sugars in the reserve pool into structural dry matter is accompanied with a loss of biomass, called growth respiration. Growth respiration is dependent on the chemical composition of the synthesized tissue. The leaf area of the crop is found after division of the green leaf weight of the crop by the specific leaf weight. Increase in leaf area and the subsequent light interception are part of the main feed back loops in the model. Root and leaves die off after a certain period. Harvested pods are the yield component of crop growth. Assumptions concerning the most important processes modelled and selection of parameters are detailed below.

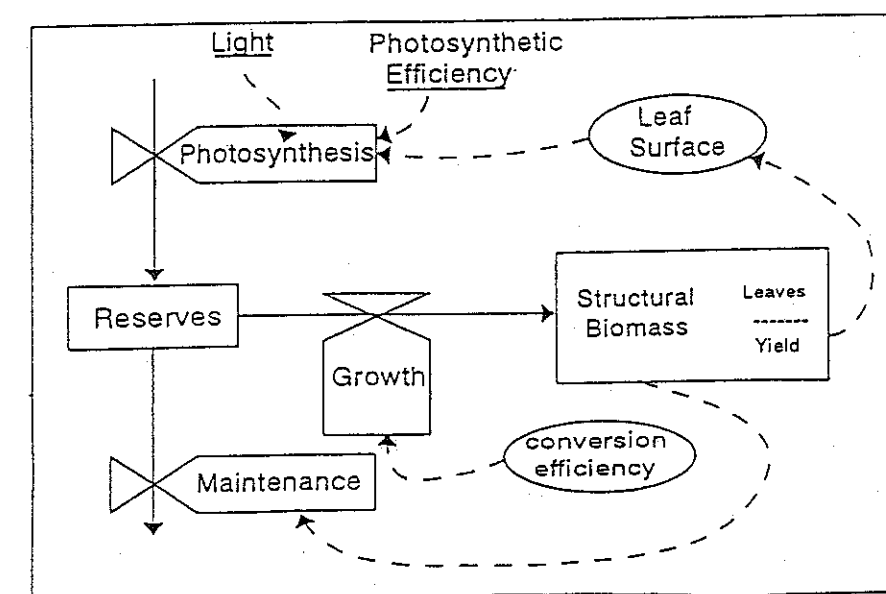


Figure 1  
Relational diagram for the primary production of cocoa

### Light Interception

Light transmission in canopies follows an exponential profile in accordance with Beer's law, the rate of interception depends on the amount of leaf area and the light extinction coefficient of the crop. Light extinction coefficients in the order of 0.54 to 0.67 were found by Alvim (1977). Yapp and Hadley (1991) found higher values from 0.61 to 0.96 in young, high density cocoa in Sabah. Light interception was calculated subsequently making use of the routines in SUCROS87 model (Spitters *et al.*, 1989), with an extinction coefficient for diffuse light of 0.6. The daily radiation was reduced homogeneously with a percentage shade of 40%. The fraction of diffuse radiation was assumed to remain unchanged.

### Leaf CO<sub>2</sub> Assimilation

Leaf CO<sub>2</sub> assimilation of cocoa trees has been investigated by many researchers, but *in situ* measurements on mature trees are relatively new. Yapp and Hadley (1991) measured light saturated rates between 6.4-8.4 mmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-2</sup> depending on genotype. Whereas Balasimha *et al.* (1991) measured rates between 2.5-6.5 mmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-2</sup> in India. A temperature effect for the leaf assimilation was reported by the latter authors. Temperatures between 31-33 °C were found to be optimal for cocoa. These studies have shown higher assimilation rates than reported previously (Hutcheon, 1977). For our model the value of 6.5 mmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-2</sup> was adopted for leaves of temperature between 31-33°C.

### Maintenance and Growth Respiration

Calculation of maintenance respiration and parameterization has remained unchanged from Anten *et al.* 1993. Growth respiration estimates for the various organs were changed because of the availability of actual tissue composition measurements by Valle *et al.* (1990). In Table 1, the glucose requirements, CO<sub>2</sub> production factors and carbon content, calculated according to Goudriaan and van Laar (1994) for cocoa tree tissues are given. The glucose requirements for the pods are the highest because of its rich fat content.

### Partitioning

Few long term growth experiments with cocoa have been made. For the S.E. Asian growing conditions the figures presented by Thong and Ng (1978), with all its shortcomings still remain one of the few available data sets. Based on the first five years a growth rate of nearly 19 ton d.m. ha<sup>-1</sup> y<sup>-1</sup> was calculated of which the fractions to roots, wood, leaves and pods were 0.08, 0.38, 0.43 and 0.11 respectively. Roots were clearly underestimated since root turnover was not included, and yield figures are on the low side compared to more modern hybrids. The partitioning table of the model showed a constant root fraction of 0.10. The pod fraction increased from 0 at the age of three years to 0.14 at the age of 8 years, at the expense of leaves which decreased in the same period from 0.5 to 0.41, and wood making up for the rest. After 8 years the partitioning factors remained unchanged.

### Specific Leaf Weight (SLW)

Some authors have investigated the specific leaf weights of cocoa, i.e. the unit leaf weight per unit leaf area. In general it has been found that leaves formed in the shade are larger and thinner (Geurs, 1971). In his study an average SLW of 5.27 mg cm<sup>-2</sup> was found. Balasimha (1985) found larger values and demonstrated important differences between clones for this characteristic. The values mentioned so far are much lower when the SLW is calculated on the basis of the data quoted by Thong and Ng (1980). In Malaysia a declining trend with age was found, but a mean value of 9.2 mg cm<sup>-2</sup> was derived. The difference with Geurs (1971) and Balasimha (1985) is probably caused by the difference in technique. The figure extrapolated from Thong and Ng (1980) includes petioles and vein tissue. In the other two studies only intraveinal tissue was more likely to be measured. The estimate from 9.2 mg cm<sup>-2</sup> was adopted for our model.



### Leaf Age and Root Turnover

In the model it was assumed that cocoa leaves die off after a certain period. Estimations of this period are rather obscure in the cocoa literature. It was assumed that within a year the canopy is entirely renewed. Tests showed that a maximum leaf age under potential growth circumstances of about 250 to 300 days were satisfactory. Since little is known about root turnover, the extreme assumption was made that this rate is proportional to the rate of leaf turnover which could be calculated from the leaf age and leaf growth rate.

### Generative Growth

Pod growth rates vary with the age of pods, as found by Hutcheon (1977). In our approach the absolute growth rates for individual pods from this study were transferred to a relative sink strength function based on cumulated degree days ( $^{\circ}\text{Cd}$ ). No pod development could take place below  $9^{\circ}\text{C}$ . Maturity of the pods was reached when a temperature sum of 2500  $^{\circ}\text{Cd}$  was cumulated (Alvim, 1977). Distribution of assimilates over the growing pods followed this relative sink strength function. Thong and Ng (1980) determined that dry beans formed 51% of the pod dry matter.

### Water Balance

In CASE2 a water module has been included. The soil water balance was represented by a simple tipping bucket model. The water balance is suited to use in environments where the soil is unsaturated throughout the year and shows a high conductivity. This model was developed by van Keulen (1975). The current version and improvements have been extensively documented by van Kraalingen (1994). Potential evapotranspiration was calculated with the Penman-Monteith combination equation. However, when shortage of water occurs the actual transpiration follows the rate of water uptake rather than potential evapotranspiration. In Figure 2 the conceptual crop growth for potential conditions has been adapted to allow for the influence of water shortages. For the physiology of the cocoa crop the translation of the effects of altered water relations on the cocoa crop are important. In SUCROS2 the direct effects are operating through: 1) a reduction of daily gross

assimilation, and 2) the root-shoot partitioning. The ratio of actual transpiration over potential transpiration was used as a measure for the degree of water stress and daily gross assimilation was reduced proportionally. This direct relationship between assimilation and transpiration has been demonstrated for cocoa as well (Hutcheon, 1977; Balasimha *et al.*, 1991). The longer term effects of water stress on partitioning do play an important role in cocoa, but these relationships have not yet been quantified adequately. In the model and increased water shortage reduces leaf ages. Possible alterations of the root shoot ratio due to water stress have not been accounted for in the current version of the model.

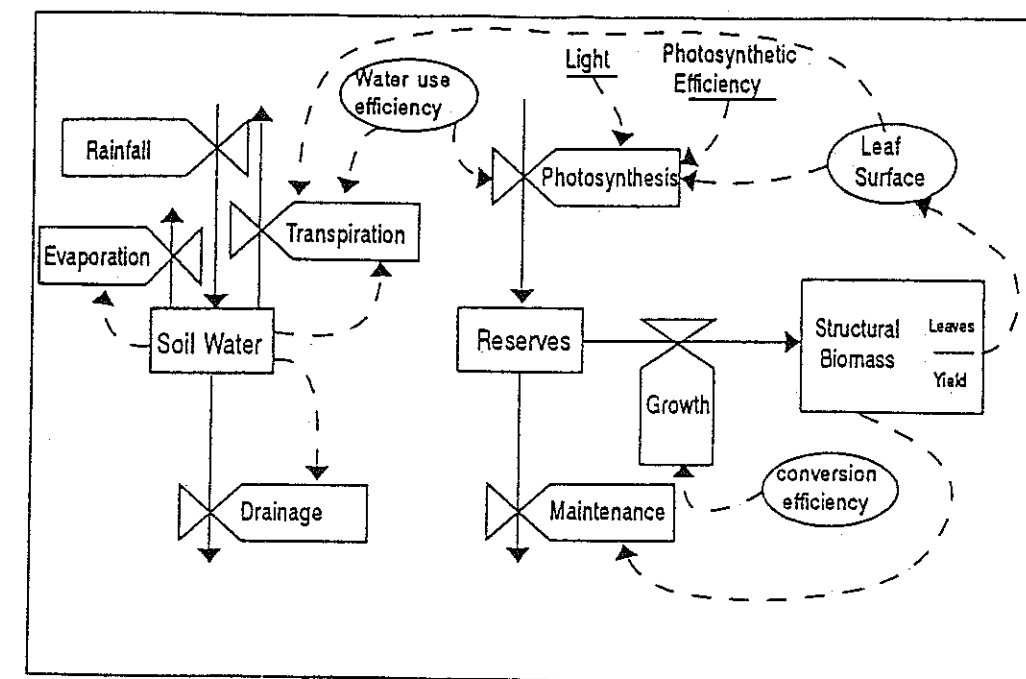


Figure 2  
Relational diagram for the water limited production of cocoa

## Driving Variables

The model for potential production (CASE1) only requires daily solar radiation ( $\text{kJ m}^{-2} \text{d}^{-1}$ ) and daily minimum and maximum temperatures as input. The model with the water balance (CASE2) uses a more extensive set of meteorological observations to calculate daily growth and production. Early morning vapour pressure (kPa), average wind speed ( $\text{m s}^{-1}$ ) and rainfall (mm) are additionally required. In this study monthly or daily data were available for three sites in different countries. These sites were located in Papua New Guinea (PNG), Dami Oil Palm Research Association at West New Britain; in Indonesia, Bah Lias Research Station in North Sumatra and for West Africa the Cocoa Research Institute of Ghana at Tafo. Daily weather variables were interpolated between monthly means, when only monthly data were available, except for rainfall. Daily rainfall patterns were generated from monthly total and number of rain days, according to the method of Geng *et al.* (1986). Radiation conditions in West Africa are lower than in SE Asia. In Ghana the 10 year average annual mean daily total shortwave radiation was  $15.08 \text{ MJ m}^{-2} \text{d}^{-1}$ , compared to 16.14 and  $17.49 \text{ MJ m}^{-2} \text{d}^{-1}$  found in Indonesia and PNG respectively. Average rainfall at the Indonesian site did not differ much from Ghana, and was about  $1400 \text{ mm y}^{-1}$ , however the distribution was more favourable in Indonesia. For PNG an average  $3500 \text{ mm y}^{-1}$  was recorded.

Physical soil characteristics required for the soil water balance are four essential points of the soil moisture retention curve for each layer of the soil. These were the moisture content (v/v) of air dry soil (pF7), at wilting point (pF 4.2), at field capacity (pF 2) and of water saturated soil (pF 0). For PNG the physical soil characteristics were determined by Warringa (1985) for Ghana these were estimated from the cocoa soils described by Wessel (1971) and for Indonesia they were obtained from Poeloengan (1987).

The model was used to calculate growth and production for a period of 10 years (1979-1988, for PNG and Indonesia and 1970-1979 for Ghana). The crop characteristics of 39 months field planted cocoa trees, given by Thong and Ng (1989) were used to initialize the model.

Table 1

Biochemical composition in structural components of cacao leaves, roots, wood, flowers, cherelles and pods and the corresponding carbon content (C) [ $\text{g C g}^{-1} \text{d.m.}$ ], glucose requirement (G) [ $\text{g CH}_2\text{O g}^{-1} \text{d.m.}$ ] and  $\text{CO}_2$  production factor ( $\Phi$ ) [ $\text{g CO}_2 \text{g}^{-1} \text{d.m.}$ ]. Based on Goudriaan & van Laar (1994) and Valle *et al.* (1990)

	Carbo-hydrates	Protein	Lipids	Lignin	Organic-Acids	Minerals	C	G	$\Phi$
C	0.4504	0.5321	0.7733	0.6899	0.3746	0.			
G	1.242	2.00	3.106	2.174	0.929	0.05			
$\Phi$	0.170	0.982	1.720	0.659	-0.011	0.073			
Leaves	0.53	0.25	0.05	0.05	0.06	0.06	0.467	1.481	0.458
Wood	0.49	0.02	0.01	0.38	0.05	0.05	0.520	1.555	0.374
Roots	0.57	0.02	0.01	0.30	0.05	0.05	0.501	1.480	0.335
Flowers	0.73	0.14	0.02	0.03	0.00	0.08	0.442	1.332	0.331
Cherelles	0.73	0.14	0.01	0.05	0.03	0.05	0.455	1.353	0.315
Pods	0.59	0.13	0.18	0.05	0.05	0.05	0.509	1.666	0.577

## RESULTS

With unchanged parameter sets it was possible to calculate yield profiles in different countries for periods up to 25 years. (Influence of weather, soils and standing biomass on the growth and death rates of the crop where in balance with each other, both under potential circumstances and when water limitations occurred). This dynamic balance could be maintained for extensive periods. Apart from the yearly yields, the results of the most important state, rate and intermediate variables are presented.

Dry matter production under potential conditions in Ghana, Indonesia and PNG was strongly related to the radiation recorded at those sites (Table 2). The reduction in production due to water stress was strongest in Ghana, followed by Indonesia and only mild reductions were calculated for PNG. The yields from those sites had the same ranking as total dry matter production (Table 3). The highest pod yields were calculated for PNG and the lowest for Ghana. In Figure 3 the pod yields for all three sites over ten years has been

given, for both the potential and water limited production situation. At all sites the increase in production for 5-10 years after planting is clear. After the first 9 to 10 years differences in yields between years under potential conditions are small. For the water limited production, the yields are nearly always lower than for the potential production scenario and much more variable between the years.

Table 2  
Average total dry matter production (ton d.m. ha<sup>-1</sup> y<sup>-1</sup>) at three selected sites in Ghana, Indonesia and Papua New Guinea under potential (level 1) and water limited (level 2) conditions

Production-level	Ghana	Indonesia	P.N.G.
1	23.6	24.6	25.7
2	15.1	20.0	24.3

Table 3  
Average pod yield (ton d.m. ha<sup>-1</sup> y<sup>-1</sup>) at three selected sites in Ghana, Indonesia and Papua New Guinea under potential (level 1) and water limited (level 2) conditions

Production-level	Ghana	Indonesia	P.N.G.
1	2.5	2.6	2.7
2	1.6	2.1	2.6

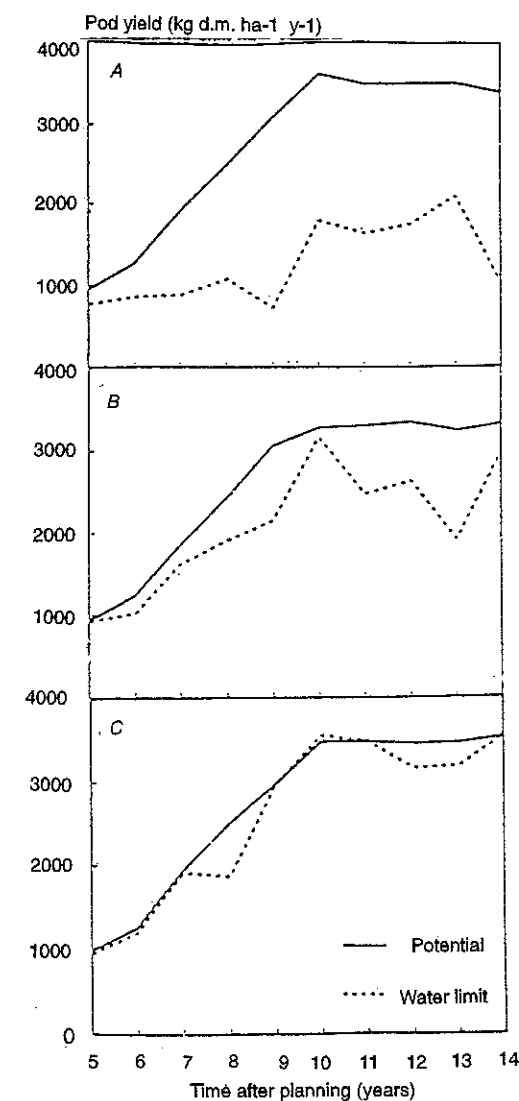


Figure 3  
Simulated pod yields (kg d.m. ha<sup>-1</sup> y<sup>-1</sup>) in Ghana (A), Indonesia (B) and Papua New Guinea (C) under potential and water limited conditions

To explain the differences in dry matter production and pod yields, the average daily gross photosynthetic production, maintenance respiration *i.e.* sugars lost to maintenance of the living biomass, and LAI, are given in Tables 4, 5 and 6. Photosynthetic production ranged from 170 to 190 kg CH<sub>2</sub>O ha<sup>-1</sup> d<sup>-1</sup> from Ghana to PNG. The average reduction in daily photosynthetic production due to water stress was 43, 15 and 5% for Ghana, Indonesia and PNG respectively. Water stress increased the difference in daily photosynthetic production between the sites. Maintenance respiration showed small differences between the sites under potential conditions, these were enhanced due to water stress. The difference in LAI under potential conditions between the sites is very small. In Fig. 4 the time course of LAI for the three sites is given. Variations due to water shortages are very explicit in Ghana. The water

limited time course of LAI in PNG is for most of the time equal to the potential line, with the exception of the 8th year.

Table 4

Average daily gross photosynthetic production ( $\text{kg CH}_2\text{O ha}^{-1} \text{d}^{-1}$ ) at three selected sites in Ghana, Indonesia and Papua New Guinea under potential (level 1) and water limited (level 2) conditions

Production-level	Ghana	Indonesia	P.N.G.
1	173	181	190
2	95	145	178

Table 5

Average daily maintenance respiration ( $\text{kg CH}_2\text{O ha}^{-1} \text{d}^{-1}$ ) at three selected sites in Ghana, Indonesia and Papua New Guinea under potential (level 1) and water limited (level 2) conditions

Production-level	Ghana	Indonesia	P.N.G.
1	73	75	82
2	30	59	75

Table 6

Average Leaf Area Index ( $\text{m}^2 \text{leaf m}^{-2} \text{soil}$ ) at three selected sites in Ghana, Indonesia and Papua New Guinea under potential (level 1) and water limited (level 2) conditions

Production-level	Ghana	Indonesia	P.N.G.
1	7.34	7.67	7.97
2	3.60	5.75	7.33

## DISCUSSION

Total dry matter production under water limited conditions as calculated for Indonesia of 20 ton d.m.  $\text{ha}^{-1} \text{y}^{-1}$  are close to the observed production of 18.9 ton d.m.  $\text{ha}^{-1} \text{y}^{-1}$  under Malaysian conditions by Thong and Ng (1980). Potential production was by far the highest in PNG, which could be expected on the basis of the higher radiation recorded at that site. For Ghana which experiences much lower radiation the potential production was the lowest. The reduction of potential dry matter production due to water stress was 19% for the site in Indonesia. For PNG the gap between potential and water limited production was much smaller. A 36% reduction in total dry matter production due to water limitations was calculated for Ghana.

Pod yield for all three sites at both levels of production were around 11% of total dry matter production. With a percentage dry beans of 51%, the yields averaged over the ten years were only in the order of 1 to 1.3 ton dry beans  $\text{ha}^{-1}$  for Indonesia. Modern hybrid material has yielded already more than calculated with these versions of the model. Production in PNG was calculated to be higher but still not up to the level as reported for experiments in Malaysia. For Ghana comparisons with the second shade and manurial trial (Ahenkorah *et al.*, 1987) show that under 'moderate' shade on average 1 ton dry beans  $\text{ha}^{-1} \text{y}^{-1}$  could be harvested. Based on the current assumptions the model calculated 0.8 ton  $\text{y}^{-1}$  for the water limited yield. Under not limiting conditions this was 1.25 ton  $\text{y}^{-1}$ . It is important to note in the model it was assumed that flowering was spread over the whole year. This results in less marked harvesting periods within a year as observed with modern hybrid material. This is in contrast to the older Amelonado plantings of West Africa which show a much stronger rainfall-synchronized flowering and harvest period. When the first years of pod yields in all three instances of Figure 3 are compared to the actual yields obtained with modern hybrid material under good management it appears that the model produced rather low figures. The yields after 9 to 10 years are comparable to yields obtained under commercial conditions. The precocity of modern hybrids was thus underestimated with the model.

The calculated LAI, ranging from an average of 7.3 for Ghana to nearly 8 in PNG, is on the high side. Hence, Thong and Ng (1980) quoted LAI values of 10. Alvim (1977) quoted LAI

values for cocoa between 4 - 6. Whereas Hutcheon (1977) quoted fluctuations in LAI for a stand of cocoa due to water stress between 2 and 8. These fluctuations compare well with the water limited LAI for Ghana presented in Figure 4A. A substantial portion of the assimilates is respired to form new leaves maintaining the high LAI values. Also the maintenance respiration requirements of this large biomass of leaves is assimilate costly. Both processes are at the expense of pod yield.

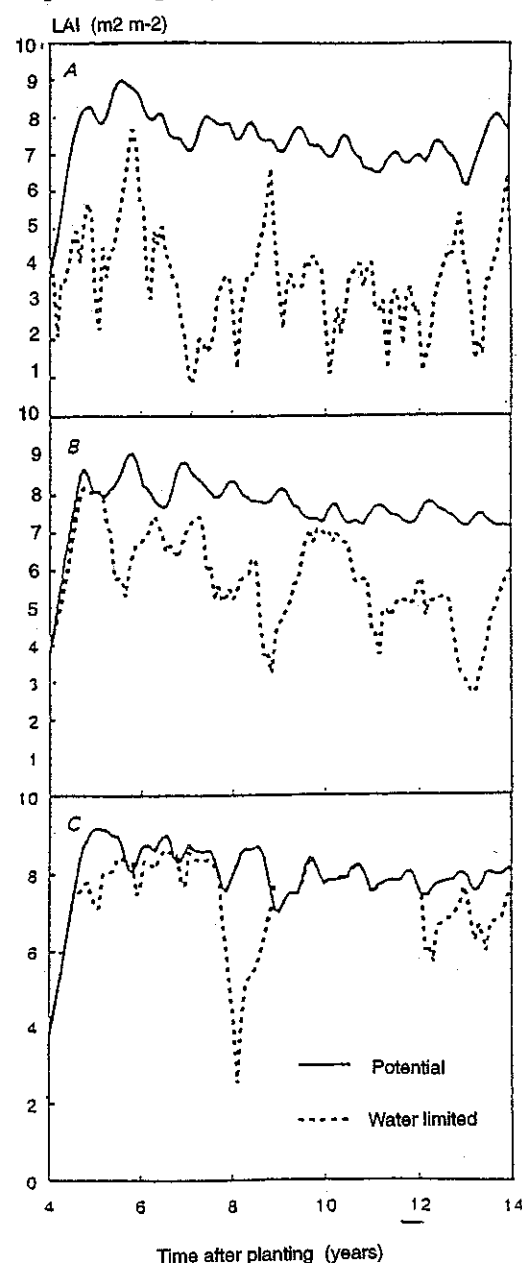


Figure 4

Leaf area indices for Ghana (A), Indonesia (B) and Papua New Guinea (C) under potential and water limited conditions

Water stress acts in two ways on growth and yield of cocoa in our model. A direct reduction of crop photosynthesis in the first place. Secondly, water stress acted its influence through a reduced LAI, due to early leaf fall. During a period of severe water stress a new balance between photosynthesis and maintenance respiration is found. Due to the reduction of the leaf biomass, the maintenance respiration was lower. Lower pod loads on the trees in water limited situations have also a beneficial effect on the reduction of the maintenance respiration. These reduced maintenance respiration requirements, could still be met by the lower photosynthetic production. Slow growth rates were the result. The lower LAI during periods of water stress has also a positive effect on lowering the transpiring surface area, alleviating the transpiration requirements.

The current model formulation and choice of parameters showed that it was possible to make physiological relations quantitatively explicit. The results indicate that partitioning of assimilates to the leaf and pod fractions were respectively over and under-estimated. The order of dry matter production calculated with the model showed a good relationship with dry matter production in Malaysia. The low yields calculated with the model are thus the result of the overestimation of the amount of assimilates partitioned to the leaf fraction. In Costa Rica higher pod partitioning factors of dry matter were found for cocoa under *Cordia* and *Erythrina* shade (Fassbender, *et al.*, 1988). Yapp and Hadley (1991) also presented evidence for higher partitioning factors in some cocoa varieties.

The current model makes hypotheses of cocoa growth and production quantitatively explicit. Growth and production of cocoa under non-limiting conditions, as well as under water-limited conditions was described adequately. The results give us a greater insight in the physiological processes determining and limiting growth and yield. Improvements can be made when the effect of mineral nutrition on photosynthesis and leaf age, and the effects of water stress on nutrient availability are taken into account as well.



To conclude it should be emphasized that the primary goal of our exercise is to describe rather than to predict. A quantitative description of cocoa physiology helps researchers to focus their attention on gaps in our knowledge. And secondly, a quantitative model enables the evaluation of decisions beforehand.

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