The water relations in cacao (*Theobroma cacao* L.): Modelling root growth and evapotranspiration.

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Abstract

In Togo, West Africa the government wants to increase the cashcrop production. The Togolese government hoped to achieve this yield increase by optimizing the use of phosphate rock. Optimizing the use of phosphate rock is not done to achieve maximum yields, but to achieve maximum efficiency of the uptake of other fertilizers.
Knowledge about the attainable production is needed to optimize the use of phosphate rock. For cacao this knowledge can be gathered using the simulation model called CASE2, which was developed by Wouter Gerritsma. In this thesis the water relations of cacao are studied, especially the root growth and the evapotranspiration. A theoretical framework was defined to simulate the attainable yields of cocoa in West Africa. There are no yield data available from observations for a period where weather data are available. Therefore it is not possible to verify the simulation model.

The root system of cacao is characterized by a taproot with elongating lateral roots. The taproot anchors the tree and can penetrate the soil up to 2-2.5 m. The density of the lateral roots decreases exponentially with depth. Twenty percent of the lateral roots is able to take up water.

Version 1.2 of CASE2 includes the following assumptions:

- The length of the taproot determines the depth at which water can be taken up.
- There is a relation between length and weight of the lateral roots, which can be used to calculate the root area.
- The water uptake in a soil layer is proportional to the fine root area in that layer.

Most often cacao is cropped under shade trees. It was not possible to model the roots of the shade trees similar to the roots of cocoa, because of the huge variety in shade policy. The cocoa model does not account for water competition in the model.

In version 1.1 evapotranspiration of cocoa is modelled as a short grass surface. In version 1.2 the evapotranspiration is calculated for trees. The results of both methods differ less than ten percent.

The simulation results of both versions fit well with the observed yearly yield in Malaysia. Under Malaysian conditions there seems to be no difference between the two versions. Water is the limiting factor, but apparently water stress is described quite well. The distribution of rain is an important factor.
Under Ghanaian conditions both versions differ. Version 1.2 is more sensitive to the distribution of rain throughout the year.

The partitioning of assimilates is constant throughout the year. This is not realistic in a situation after leaf fall. Therefore in version 1.3 a LAI-dependent partitioning of the assimilates is included. The results of version 1.3 show that the trees recover more quickly after a dry period.

Samenvatting

De overheid in Togo, West Afrika wil een impuls geven om de cashcropproductie in dit land te verhogen. Het is de bedoeling om de gewenste productieverhoging te bereiken door het fosfaatgebruik te optimaliseren. Doel is niet om hiermee een maximale opbrengst te halen, maar om maximale efficientie van opname van andere nutrienten te bereiken.
Om het fosfaatgebruik te kunnen optimaliseren is er kennis nodig over het niveau van de bereikbare opbrengst. Dit bereikbare niveau is voor cacao berekend door gebruik te maken van een simulatie model, genaamd CASE2, ontwikkeld door Wouter Gerritsma. In dit afstudeervak zijn de waterrelaties van cacao bestudeerd, in het bijzonder de wortelgroei en evapotranspiratie. Er is een theoretisch raamwerk geformuleerd om de opbrengst van cacao in West Afrika te simuleren. Een dataset voor West Afrika waarin zowel gemeten opbrengsten als klimaatgegevens beschikbaar zijn ontbreekt. Daardoor kan het simulatiemodel niet geverifieerd worden.

Het wortelsysteem van cacao wordt gekarakteriseerd door een penwortel met daaraan ontspringende zijwortels. De penwortel kan tot 2-2.5 m diep reiken en dient voor de verankering van de boom. De dichtheid van de zijwortels neemt exponentieel af met de diepte. Twintig procent van de zijwortels is in staat tot de opname van water.

In de nieuwe versie van CASE2, versie 1.2, resultaat van dit afstudeervak, zijn onder andere de volgende aannamen over het wortelstelsel gedaan:

- De lengte van de penwortel bepaalt de diepte tot waar water kan worden opgenomen.
- Er is een relatie tussen lengte en gewicht van de fijne wortels, waardoor het worteloppervlak berekend kan worden.
- De wateropname in een bodemlaag is evenredig met het oppervlakte van de fijne zijwortels in die laag.

Cacao wordt meestal geteeld onder schaduwbomen. Het was niet mogelijk om de wortels van de schaduwbomen op dezelfde wijze te modelleren als voor cacao gedaan is, omdat er veel variabiliteit is. Watercompetitie is niet meegenomen in het model.

In versie 1.1 wordt de evapotranspiratie beschreven als ware de canopy een "short grass surface". In versie 1.2 wordt de evapotranspiratie berekend betreffende bomen.
De resulaten van beide methoden liggen minder dan tien procent uit elkaar.

Voor de Maleisische situatie benaderen beide versies van het model de gemeten jaaropbrengsten goed. Er is nauwelijks verschil tussen de twee versies. Water speelt wel een rol. De beschrijving zoals in versie 1.1 lijkt in Maleisie te voldoen om de watergelimiteerde opbrengst te berekenen. In de Ghanese situatie verschillen de modellen wel. Versie 1.2 is gevoelig voor de verdeling van de regenval binnen een jaar.

De verdeling van de assimilaten is constant gedurende een jaar. Dat is niet realistisch in een situatie waarin de bomen weinig blad dragen. In versie 1.3 is een LAI afhankelijke verdeling van de assimilaten verondersteld. De resultaten van de simulaties van versie 1.3 laten zien dat de bomen sneller herstellen na een droge periode.

1 Introduction

In Togo, West Africa the government tries to improve the farmer's situation by investigating the possibilities to improve cash crop production. One of the objectives is to optimize phosphate rock (PR) use on cacao, cotton and coffee, not to reach maximum yields, but to reach maximum efficiency of other fertilizers. As phosphorus is a limiting nutrient in almost all cash crop suitable soils, there is an urgent need to know the amount of PR required to improve the minimum P-availability. PR must be seen as an amendment.

To be able to interpret the data on optimizing phosphate rock, knowledge of water limited production of these crops is required. Therefore this thesis focuses on the water relations of cocoa *(Theobroma cacao)* and how to model root growth and evapotranspiration.

Shortage of water is the most important factor affecting the physiology and the yielding capacity of cacao in West Africa. Leaf production, leaf expansion, leaf fall, cambial growth, flowering, fruit setting, cherelle wilt and pod growth are all affected by the plant-water potential (Hutcheon, 1977). There is a need to study the influence of water stress on development and yield in cacao over some years, in more detail. In this report two aspects on cocoa growth are studied: evapotranspiration and the growth of roots.

Evapotranspiration
The water balance is the result of a complex interaction between the soil-water balance, canopy energy balance and transpiration. The latter component needs special attention: In general tree crops have a higher level of transpiration than annual crops. In most tree crops the leaves are present throughout the entire year, whereas annuals leave the soil bare during the dry season. Another reason for the higher rate of evapotranspiration is that the aerodynamic resistance of tree crops is smaller. The lower aerodynamic resistance of cocoa, compared to wheat for example is caused by its height. Wind blows easier through the canopy of cacao than through the canopy of wheat.

Water competition
Because cacao trees are mainly grown as intercropping systems (Herzog, 1992), there is competition for resources between the cocoa and shade trees. The partitioning of the small amount of water available depends on the distribution of roots of the cacao tree and the shade tree.
The roots of cocoa were studied in this thesis. The root distribution of cacao can be characterized as a dense mat with one tap root, which anchors the tree in the soil. The water uptake of cocoa through its roots from different soil layers was quantified.
It is difficult to study the roots of the shade trees. On average 5.4 shade tree species are planted per hectare (Herzog, 1992). Each species has different properties: most shade trees are wild forest species yielding many different products. Because of the great variability of species and the random distribution of the shade trees on a plantation, it was not possible to quantify the water competition between the cocoa and the shade trees.

Other factors
Growth of cacao is very complex and not only determined by water relations. The partitioning shade-no shade of the plantations needs to be taken into account as well. Light- and water limitation have an effect on the availability and uptake of nutrients. Nutrition of cacao should always be determined in relation to shade conditions, as shown by Ahenkorah *et al.* (1974) in the well known shade and manurial experiments in Ghana. Shortage of water decreases nutrient uptake (Keltjens & Nelemans, 1998), P-availability is low, and therefore growth and yield will decrease. In this thesis it was too complicated to model all these factors affecting cocoa-growth in great detail.

The aim of this thesis is to study the water relations of cacao and to include these relations in an existing model CASE2. Especially the evapotranspiration component, root growth and root distribution are studied.

Outline of this report:
In this thesis three methods to gather knowledge about cocoa were used: literature research, model simulation and visit to the field.

Literature research was done to find more about the water balance of cocoa.
In chapter 2 in section 1 the botanical characteristics of *Theobroma cacao* are described shortly. In section 2 the environmental conditions for cocoa in West Africa are described. Climate, soils and shade are also discussed here.
Chapter 3 deals with the water balance of cacao. The theory of calculating the evapotranspiration is explained. The Penman Monteith equation is important in this context. The differences between annuals and perennials in modeling evapotranspiration are described. The last section of chapter 3 is about the roots of cocoa and answers the following questions. How are the roots of a cacao tree distributed? What is the distribution of roots of the shade species? Plantations can be considered as agroforestry systems. Is it possible to model such a variability?

The simulation model CASE2 (Cacao Simulation Engine 2) was used to calculate growth and yield for West African conditions. The model is based on universal plant and crop physiological relations. Radiation and air temperatures are the main driving parameters for the model.
In version 1.1 of the model is included the effect of water limitation, but only using the basic principles of water stress. The water limited production had to be calculated more accurately for cacao. The water balance of cacao is extended in version 1.2. The evapotranspiration-component is transformed for a tropical crop tree. In version 1.2 root growth of cocoa is modelled more elaborately than in version 1.1.
The model is described in chapter 4 of this report. The results are discussed in chapter 5. A listing of the model can be found in Appendix 1a.

The International Fertilizer Development Center in Africa (IFDC-A) was visited from the 26th of May until the 24th of June 1998. The goals of that visit were:

- Contacting people with expertise in Togelese agriculture, soils and climate.
- Visiting cocoa plantations of farmers and research stations in Togo and Ghana, to understand cacao and it growing conditions better.

The report of the visit to Togo and Ghana can be found in Appendix 2.

2 The plant *Theobroma cacao* L.

In this chapter some botanical characteristics of cacao and environmental conditions required for the successful cultivation of the crop will be explained. In section 2.1 the plant will be described. In section 2.2 the environmental conditions will be explained: climate, soil, and shade requirements.

2.1 The botany of cacao

Introduction
Cacao (*Theobroma cacao* L.) is a native species of the rain forests of South America. The origin is considered to be the basin of the Upper Amazon. The genus *Theobroma* consists 22 species. *Theobroma cacao* L. is the only species of the genus that is cultivated commercially on a world scale. The genus *Theobroma* is member of the family of *Sterculiaceae*. This genus is indigenous to South America, from southern Mexico to Brazil and Bolivia.

Roots
Cocoa seedlings develop a taproot. It will reach 80 cm within five years, and under good conditions the tap root will penetrate deeper soil layers, up to a maximum of 2 – 2.5 m (SOFRECO, 1991). In an early stage many lateral roots arise, just below the collar. In a mature tree most of the fine, secondary roots are found within the first 15-20 cm of the collar (Wood, 1975). The root distribution of cacao can be characterised as a dense mat of lateral roots with one taproot, which anchors the tree. The taproot is essential for water and mineral uptake in dry periods (Kummerow *et al.*, 1981).
The majority of the roots develop in the upper layer of the soil, close to the litter layer. The soil fertility of most tropical soils is concentrated in this soil and litter interface. Tropical tree species often have a root mat (Breman, 1992). A dense mat of superficial roots intercepts the released nutrients most effectively. McCreary *et al.*(1943) found a positive relationship between thickness of the rooting zone and of the humic soil layer. He described the root system of cacao in a physiologically shallow soil as mainly superficially, and that of a physiologically deep soil as well dispersed. The term 'physiological depth' is related to "the thickness of the layer of the soil that is adequately aerated and structurally suitable for unrestricted growth of roots". (Hardy, 1960). A depth between 1.5 and 3 m is best (Are & Gwynne-Jones, 1974).

Some soils restrict full development of the rooting systems, because of superficial unpenetrable layers or parent rock material within 1 m of the surface (SOFRECO, 1991; Radersma, 1996).

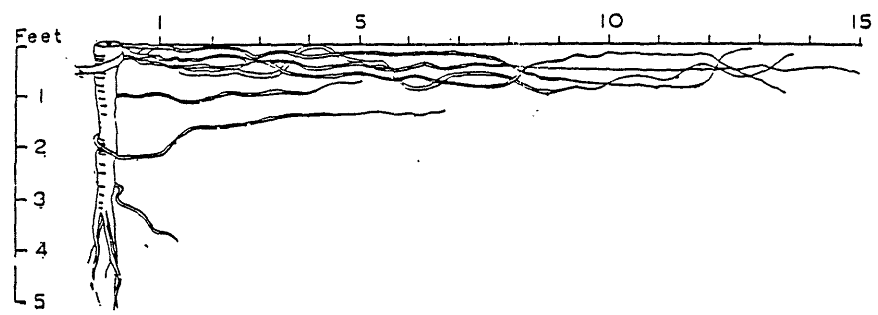


Figure 2.1.1: The root system of cocoa (McCreary, 1943)

Trunk and branches
The top of the canopy of cocoa trees can reach to a height of 8 to 10 m. The pattern of growth is characteristic. Cocoa branches in "storeys". Seedlings grows as a single stem till up to 1.5-2 m. Then three to five lateral branches appear and together these 'fan' branches form the so-called jorquette. Below the jorquette 'chupon'-branches develop from a bud. They give height to the cocoa tree. When their length is around 1 m, they form a new jorquette, one level higher.

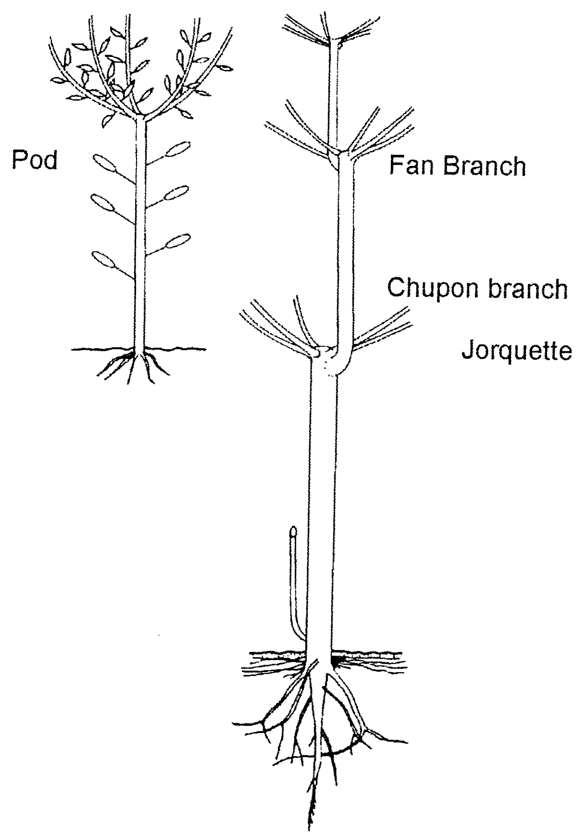


Figure 2.1.2: The stem and branches of cocoa (Wood, 1975).

Leaves
The production of leaves is in a series of flushes. Leaf growth is a discontinuous process. The terminal bud shoots and produces three to six leaves rapidly. These leaves hang vertically, are very soft and tender and have a red colour. They are very sensitive to diseases and insects. But soon they harden, turn green and take an "upright" position. After the flush has expanded, the bud remains dormant until internal or environmental factors induce a new flush.

Flowers and fruits
The flowers grow directly on the old wood of the stem and the branches. On certain places on the wood, the so-called cushions, 5-15 delicate, pink-whitish flowers appear. The flower is long-pedicilled. Five is the basic number for the complex structure of the flower: five free sepals; five free petals; ten stamens in two whorls, of which only one is fertile; and an ovary of five united carpels (Wood, 1975).
The structure of the flower and the stickiness of the pollen exclude pollination by wind. Small insects of the genus *Forcypomia*, family *Ceratopogonidea* are the most important pollinators (Wood, 1975; Dossa, pers. com.)

After a compatible pollination the fruit starts to develop. A young fruit, up to three months is called a 'cherelle'. Up to 80 percent of these cherelles will not reach maturity, because of 'cherelle wilt'. Which means the small fruit dries, turns black and will fall off. Cherelle wilt is the physiological phenomenon that results from competition for water and carbohydrates and mineral nutrients between the young fruit, the older crop and the vegetative growth. After three months the fruit has passed the most critical stage. Within another three months the fruit, usually called pod, will grow into maturity. When the pod is ripe, it turns from green till yellow-orange in the Amelonado and Amazon cocoa. There is a great range in size, shape and colour of the pods. They vary in size from 10-30 cm. Different varieties of *Theobroma cacao* L. produce different shapes of pods. One pod contains many seeds, as little as 20, but sometimes as many as 50. The seeds are surrounded by a layer of 'pulp', which has a high content of sugar and mucilage. The high sugar content is important in the fermentation process. Both fermentation and drying of the beans give the beans the special chocolate flavour.

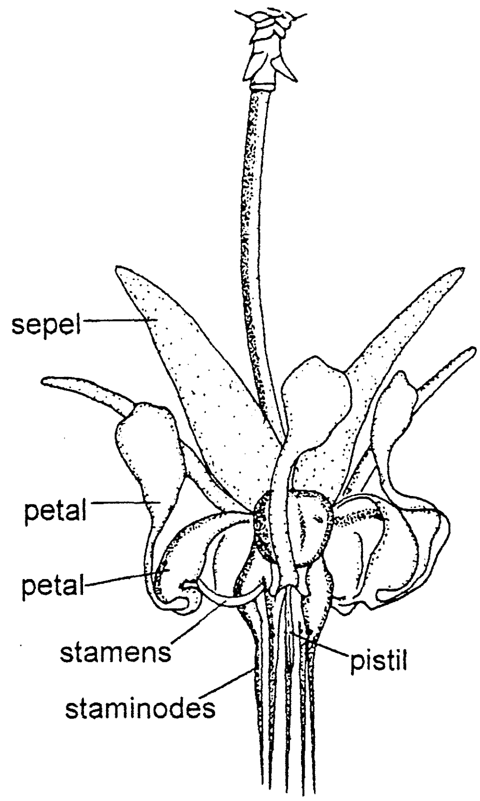


Figure 2.1.3: The flower of cocoa (Wood, 1975).

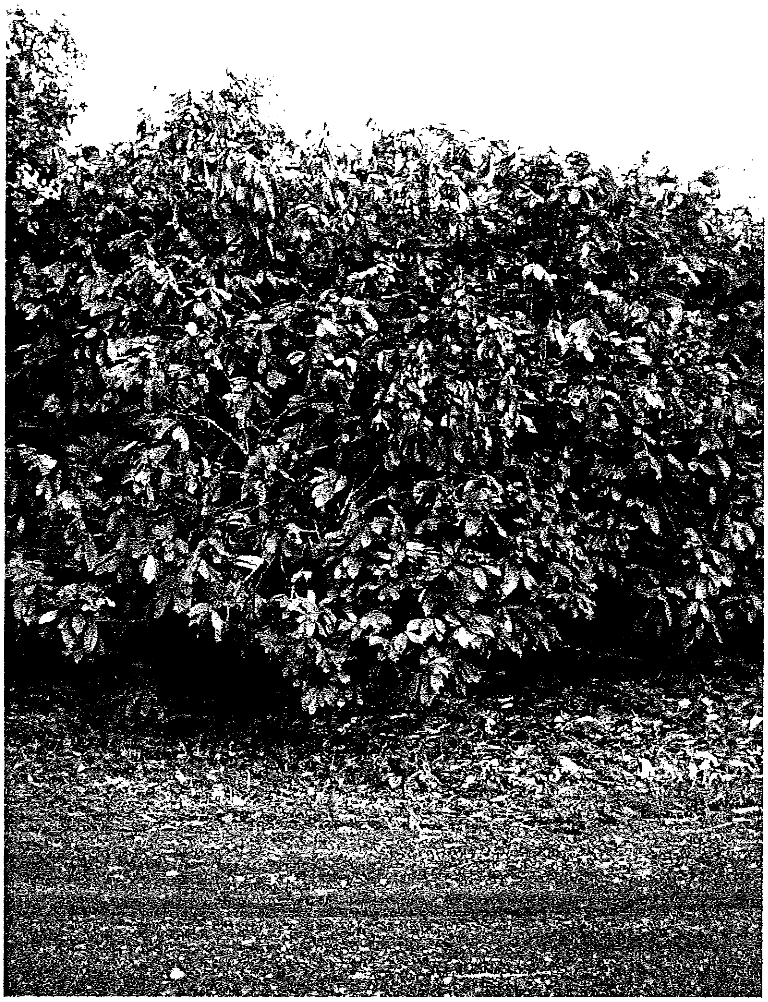


Photo 2.1.1: Cacao tree on the research plantation of IRRC-Togo, West Africa. June 1998, Liesje Mommer

Photo 2.1.2.: Flowers and 'cherelle' of cacao, growing directly on the stem. West Africa, June 1998. Liesje Mommer

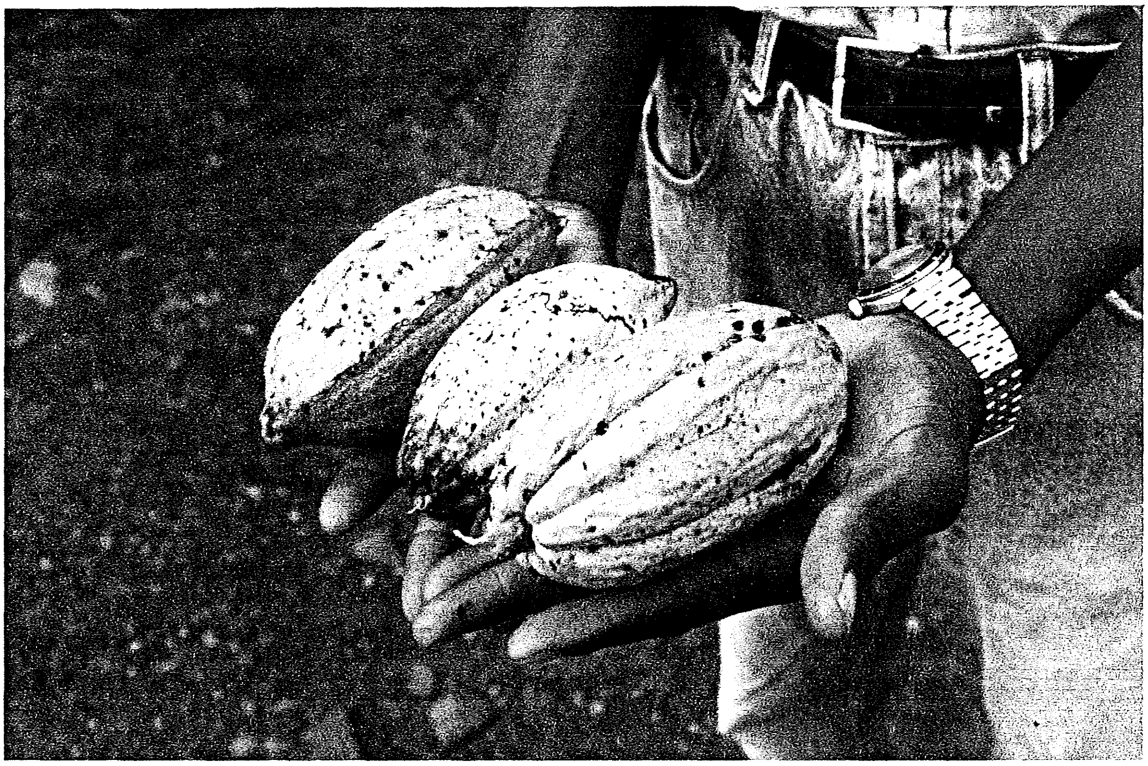


Photo 2.1.3: Cocoa pods. Togo West Africa; June 1998, Liesje Mommer

Photo 2.1.4: Beans in a cocoa pod. Togo, West Africa; June 1998; Liesje Mommer

Photo 2.1.5.: Dried beans in Ghana. June 1998; Liesje Mommer

2.2 Environmental conditions in West Africa

2.2.1 Climate

As a typical crop of the humid tropics cocoa is produced within a belt around 10° north and south of the equator.
Rainfall and temperature are considered to be the most critical climatic factors for growth of cocoa (Alvim, 1977). The natural environment of cocoa can be characterised by a high mean annual temperature, with little variation; high annual rainfall with a short dry period; high relative humidity; and low sunlight intensity.
In this chapter the West African conditions are studied.

Rainfall

The annual rainfall for Ghana (Tafo (6°15'N, 0°22'W)) is 1500 mm year. The range lies between 1150 - 1800 mm. The climate is similar in the main cocoa areas of West Africa. The rainfall is only more abundant (2500 - 3000 mm) in West Cameroon (Wood, 1975). In the cocoa growing areas of Togo the annual precipitation has declined from 1660 mm in the 60's till 1300 mm (SOFRECO, 1991). Wood (1975) states that where the annual rainfall is below 1250 mm, the moisture losses of evapotranspiration will be greater than the precipitation supplies. Cocoa in such areas can only be grown where irrigation is possible. The cocoa growing areas in Togo balance on the margins of the biophysical possibilities.

The pattern of rainfall is even more important than its annual total. The rainfall pattern in West Africa is characterised by two rainfall peaks around June and October. The peaks are separated by a brief, dry period in August. The long dry period lasts from November till March. In Ghana cocoa growing is limited to those areas that receive at least 250 mm of rain during these five months. In Nigeria the minimum rainfall in these months is only 180 mm (Wood, 1975). That cocoa is still growing in Nigeria is due to differences in temperature, soil texture and humidity can explain. It emphasises the point that many factors have to be taken into account when defining a suitable cocoa-growing place.

Temperature

The temperature in Ghana (Tafo) usually lies between a maximum of 29 to 33°C and a minimum of 20 to 22°C. Similar data are found in other cocoa growing areas in other West African countries.
Data from Ghana and Nigeria show mean monthly maxims of 33.8 respectively 32.5°C. Hardy (1960) suggested a maximum temperature, given as mean monthly maximum of 30°C. The cocoa plantations in West Africa counter the argument of Hardy.
Some researchers concluded that mean monthly minimum temperature for successful growth of cocoa is 15 °C, and the absolute minimum was 10 °C. But Alvim (1977) observed a temperature drop to 4 °C, and reported that the trees were not irreversibly damaged.

The effect of temperature on growth and flowering of cocoa has been studied in many different situations, in many different places, in the field and laboratory, on seedlings and mature trees. There are many hypotheses, but they all are only applicable in a specific situation. Field data collected in Ghana led to the theory that flushing is suppressed when the daily maximum temperature falls below 28°C (Greenwood and Possenette, 1950).

Sunlight

Often sunlight is measured in terms of sunlight hours. A more accurate method is to measure the daily total radiation. For Ghana, Accra was found (Wood, 1975):

month	J	F	M	A	M	J	J	A	S	O	N	D	year
sunlight (hours)	6.8	7.2	7.0	7.2	6.8	5.2	4.5	4.5	5.7	7.1	8.1	7.6	6.45
solar rad (MJ/m2)	15.2	18.3	20.2	20.3	19.7	16.3	15.5	15.0	17.3	18.9	19.2	16.8	17.7

Table2.2.1: Daily averaged sunlight (h) and solar radiation (MJ/m2) in Ghana, Accra (Wood, 1975).

Another method to estimate the daily total radiation is to use the Ångström formula. This formula describes the relation between sunshine duration and radiation. The parameters of this regression formula were stabilished for Ghana, Tafo (Gerritsma, pers.com.).

Wind
Cocoa suffers severely from steady winds. The short petioles are easily damaged, which will lead to defoliation.
In West Africa cocoa growth is affected by the harmattan, which blows from the Sahara between December and March.

2.2.2 Soils

In this paragraph the soil characteristics required for optimal cocoa growth will be described. The "Manual for soil description and classification", of Pape and Legger (1995) will be referred to for the basic principles of soil classification. In this manual the general characteristics for soils suitable for cropping are explained.

Cocoa is successfully grown on a range of soils (Wessel, 1971a; SOFRECO, 1991; Are & Gwynne-Jones, 1974). For a good cocoa crop however, the soils must have satisfactory physical and chemical properties. Such properties must be considered in connection with climate.
The root system of cacao provides the plant anchorage and supplies nutrients and water. Cacao therefore requires a deep well-drained soil with a high nutrient content. The topsoil should be rich in organic matter (Wessel, 1971a; Alvim, 1977; Wood, 1975).
The suitability of a soil for cocoa cropping depends on soil moisture and aeration. Excess moisture reduces soil aeration and prevents free exchange of gases between soil and atmosphere. This leads to a shortage of oxygen and accumulation of carbon dioxide and eventually to reduced root respiration and less absorption of water and nutrients (Wood, 1975).
Are & Gwynne-Jones (1974) states that in good soils 60-70% of the rooted soil volume is pores.
Several authors (Alvim, 1959; Wessel, 1971a; Lemee, 1955) state that cocoa is relatively sensitive to a shortage of soil moisture. According to Wessel (1971a): "The soil must be capable of retaining an adequate supply of available moisture during all seasons, while at a time good drainage".

Texture
The best soils for cocoa contain 30-40% clay, 50% sand and 10-20% silt-sized particles. The finer particles aggregate to large very stable particles of about coarse sand size. Such soils have desirable characteristics: good for free drainage, good aeration and good for retaining a relatively high water content.
In West Africa very large quantities of gravel are often present within the soil (pers. com. Dossa; Wood, 1975). They cause bifurcation and poor development of the taproot. If the upper layer (0-30 cm) contains more than 25% gravel a soil is unsuitable for cocoa production (Wood, 1975). For the lower layers a percentage of more than 40% is unfavourable.

Nutrients
A soil suitable for cocoa cropping should be fertile and well supplied with nutrients, especially in the top layer.
The optimum P content of a soil suited for cocoa production is 100 mg kg-1 (Jadin & Vaast, 1990).
Wessel (1971a) analysed the topsoil of 17 sites in Nigeria where cocoa was grown for more than 30 years. The results showed that in most soils the minimum nutritional requirements of cocoa are met, except for P. The available P status is low in the soils of most cocoa farms. In another experiment (Wessel, 1971a) the soils at 41 cocoa farms were analysed. More than 75% of the soils contained less than 100 mg kg-1 available P and should be considered as P deficient. In

Ghana too, P deficient cocoa sites have always been reported (Wessel, 1971a). In Togo, in the Litime region most soils contain less than 15 mg kg-1 (Dossa, 1991; SOFRECO, 1991). Wessel concluded from his research (1971a) that the soils in West Africa only have a small P reserve, but large K reserves. Total N, organic P and cation exchange capacity are highly significantly correlated with the organic matter content of the soil. The organic matter content together with the pH of the soil can be considered as the most important single index of soil fertility.
See for further details about the chemical status of the soil table 2.2.1 (Wessel, 1971a).

age of cocoa (years)	pH	%C	%N	K*	Ca*	Mg*	available P (ppm)	nr of fields
0 (forest)	6.8	2.5	0.24	0.42	15.0	2.3	26	4
3 – 5	6.6	2.0	0.19	0.28	13.7	1.5	35	4
9 – 15	6.6	1.8	0.16	0.29	12.2	2.1	14	4
24 – 33	6.4	1.4	0.13	0.27	8.6	1.6	12	4

* exchangeable bases in m.e. per 100 g fine earth

Table 2.2.1: Chemical status of the surface soil (0-15 cm) and effect of cocoa cultivation. Mean values. (Wessel, 1971a)

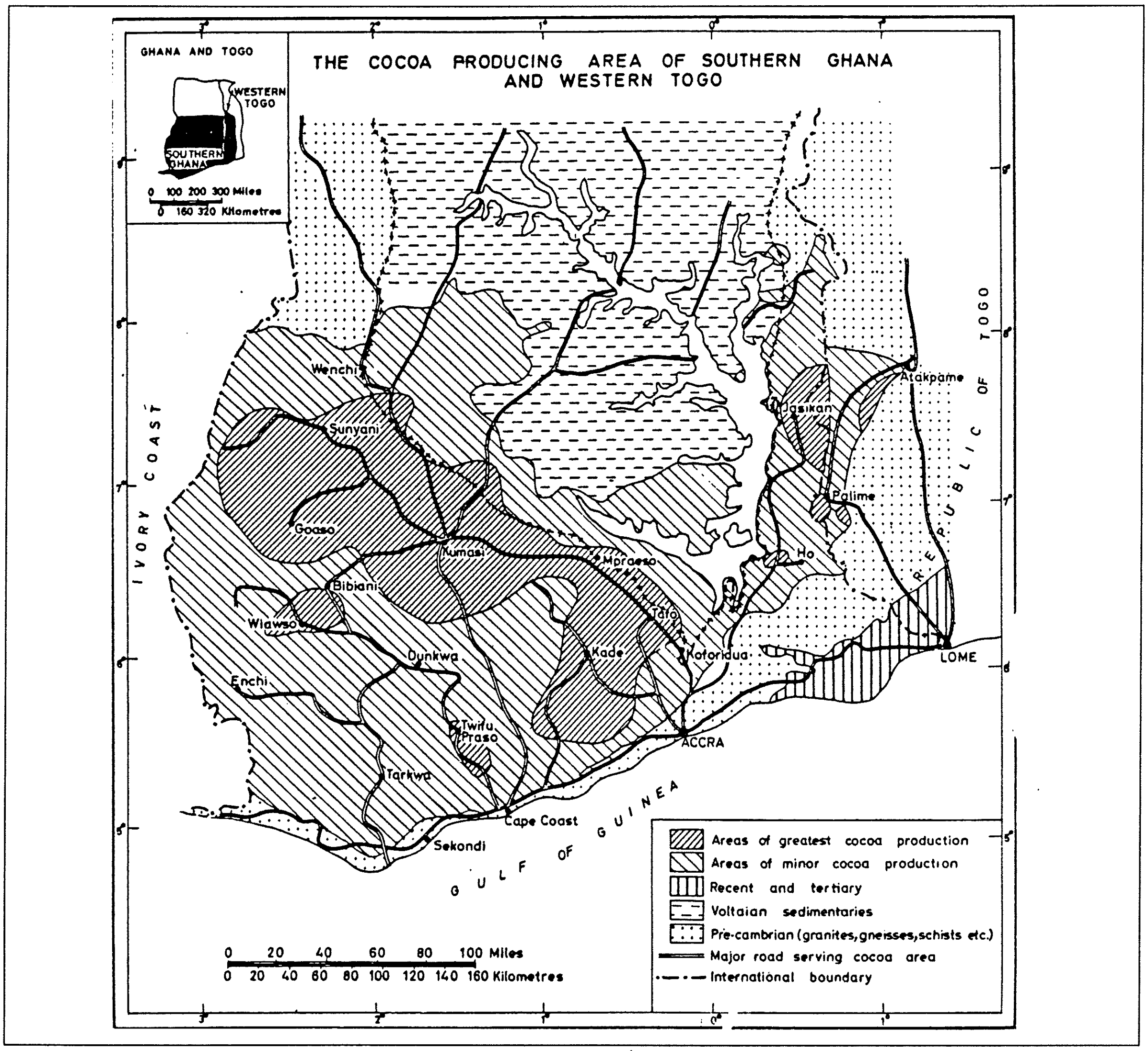


Figure2.2.1: Good soils in Ghana and Togo (Are & Gwynne-Jones, 1974, p 42)

2.2.3 Shade

It is common practice to cultivate certain tropical crops under the shade of taller trees. This kind of cultivation is often used for coffee, tea and cocoa.
The natural habitat of the cocoa plant was the lower storey of the tropical wild rainforests of the Amazon basin. Because of this origin, the argument is often used that farmers have to reproduce this habitat in the commercial growing of the crop. The light saturation of cocoa is lower than other tropical crops. Cocoa is able to reach maximum photosynthesis at lower light levels than other plants. Lemée (1955, 1956) constructed photosynthesis curves for the daily photosynthetic production. From these curves it was apparent that light saturation already occurred at 25 to 30% of full radiation.

Seedlings do not survive without shade. They must be protected against direct sunlight. In nurseries farmers create temporary shade using palm fronds or twigs as sun-shelter. In Ghana at CRIG (Cocoa Research Institute Ghana) the seedlings in polythene bags were placed under shade trees.

Mature cocoa survives under heavy shade conditions, but its yield is then only enough to ensure the survival. A cocoa grower wants to grow his crop under conditions which lead to the optimum yield. Shade must be considered in connection to nutrition. This have been done in the shade and manurial experiments at the Cocoa Research Institute of Ghana. The results of for example experiment 1, show that shade and nutrition have a complex relation.

The first cocoa shade and manurial experiment at the Cocoa Research Institute of Ghana.
The experimental trees were uniform West African Amelonado cocoa, 24 years old in May 1971. There were four treatments, each with a total of 900 trees. Shade with and without fertiliser, and no-shade with and without fertiliser situations were compared. The shade was completely removed in 1957 and a NPKMg mixture was added since October 1956. The trial lasted a period of 17 years and was located on a Rhodic Ferralsol as described in the FAO classification system (Driessen & Dudal, 1991). The details of this experiment can be found in Cunningham and Lamb (1959), Cunningham *et al.* (1961), Hurd & Cunningham (1961) and Cunningham and Arnold (1962). The complete results were published by Ahenkorah (1974).

Figure 2.2.2, shown below summarises the annual yield pattern for the entire experimental period (Ahenkorah, 1974). It is clear that the yields of treatments with fertiliser application lie above the treatments without fertiliser. The non-shaded yields are higher than the shaded yields.
The plots without fertiliser treatment have reached a plateau.

The trials without shade yielded vigorously in the beginning, as much as three times in comparison with the shade trials, but soon sharp declines followed. The peaks of both no-shade trials with and without fertiliser were very similar in time. It would be interesting to see if the yield would decline even more. Ahenkorah (1971) ascribed the senescent characteristics exhibited by the no-shade trees to nutritional stresses caused by their previous heavy cropping. On this soil, under no shade regime higher fertiliser levels should have been used to maintain high yields over longer periods. The fact that the treatment shade-fertiliser still grows continuously implies that the trees are not yet senescent. Over a long period the treatment shade-fertiliser becomes comparatively more economic (Ahenkorah, 1974).
In figure 2.2.2 the lowest curve (x---x) is the approximated national average of Ghana. The enormous gap between farm practice and the research station is caused by insufficient pruning and spraying against disease in normal farm practice.

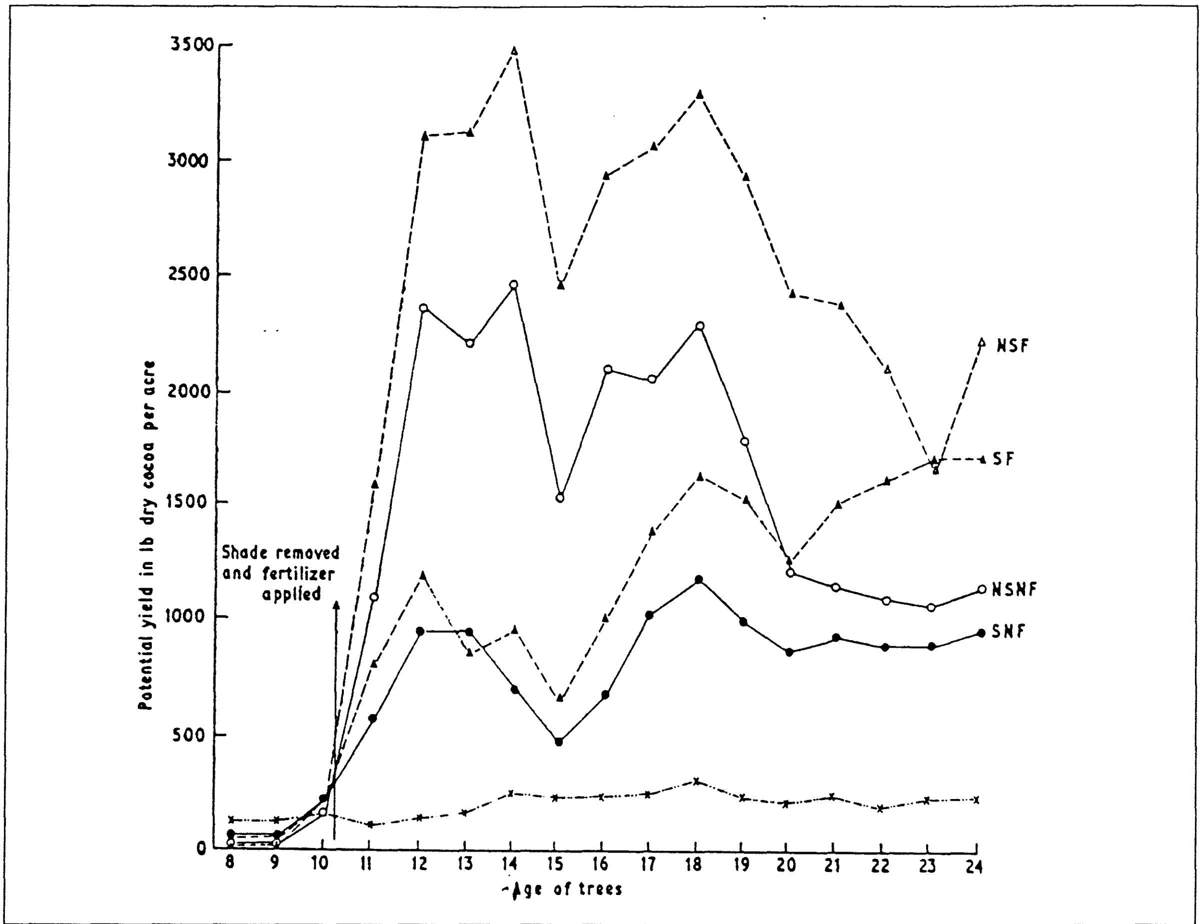


Figure 2.2.2 Effects of shade removal and fertilizer application on yield of 24-year-old cocoa. Δ---Δ no shade with fertilizer; o----o no shade no fertilizer;Δ---Δ shade with fertilizer; o---o shade no fertilizer; x----x aprox national average. (Ahenkorah, 1974).

The shade in cocoa plantations is difficult to quantify. Figure 2.2.3 illustrates the problem: The cocoa trees as well as the shade trees are not planted neatly in rows. Every plantation has its own specific map. Another aspect which makes the modelling of competition between cocoa and shade trees difficult is the large variety of species used as a shade tree. Herzog (1992) surveyed 18 cocoa and 12 coffee plantations in Ivory Coast and there he found 41 shade tree species. The mean number of different shade tree species was 5.4 species per hectare, with a range between 0-13 species per hectare (Herzog, 1992). The huge variety of secondary forest products in West Africa has an important place in the daily life of rural areas (Herzog, 1992). Farmers accept a reduction of the yield of cocoa in exchange for these shade tree products - food: e.g. fruits and palm wine, wood for fuel, and medicines. These products are not of minor in West African rural life.

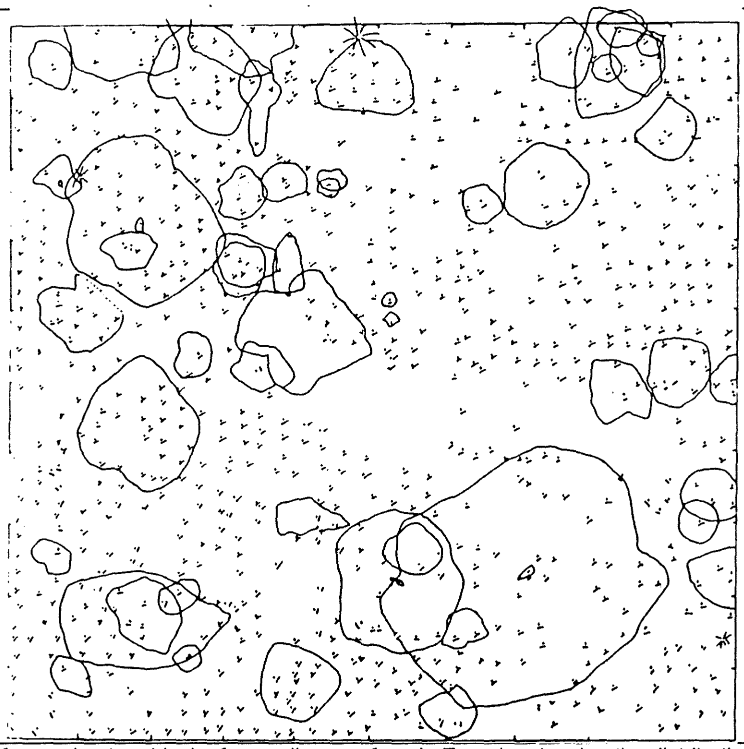


Figure 2.2.3 Plan of a one hectare block of a small cocoa farm in Equador showing the distribution of shade trees. The dots represent cocoa trees. The circles represent the canopy of the shade tree (Hadfield, 1981).

Even when there would be a map of the distribution of shade trees in a cocoa plantation, still the modelling of shade will accounts problems. The light intensities under bright and overcast conditions do not change proportional. There is a completely different light intensity pattern under the two conditions, see Hadfield (1981).

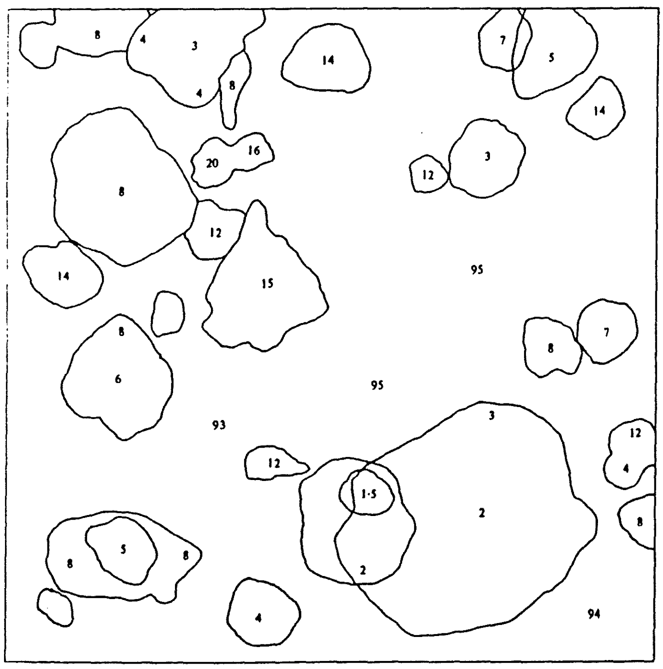


Figure 2.2.4 Light intensities as percentages of full daylight under bright conditions in the hectare of shaded cocoa shown in fig 2.2.3, between 11.00 and 13.00 h, 100%=655-770 W m-2. (Hadfield, 1981).

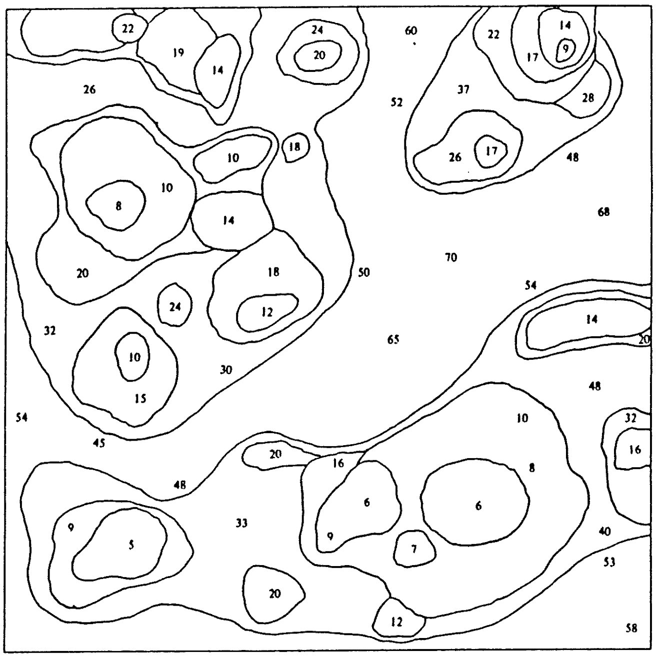


Figure 2.2.5 Light intensities as percentages of full daylight under dull overcast conditions in the hectare of shaded cocoa shown in fig 2.2.3, between 11.00 and 13.00 h, 100%=196-210Wm-2 (Hadfield, 1981).

Box 2.1 How cocoa travelled to West Africa

Cocoa is one of the most important cash crops of West Africa. Nearly all countries in this region, Ivory Coast, Ghana, Nigeria, Cameroon, Equatorial Guinea, Togo, Sierra Leone, Liberia produce cocoa beans. Today, 176 years after the introduction of cocoa on the continent, both Ivory Coast and Ghana are the world market leaders.

Cocoa was unknown to Europe until 1502, when Columbus on his fourth voyage encountered a canoe full of cocoa pods. Twenty years later the Spanish conquerors of the Aztecs found great quantities of cocoa beans in the palace Montezuma's. The beans were used as money and for making a very popular drink, called 'xocoatl'. The word 'chocolate' originated from this drink. To make the drink the beans were roasted, ground with stones and mixed with water and some other products to reduce the fat content. The Aztecs thought that the origin of the cocoa tree was the garden of one of the gods, and that it was brought to earth for the delight of man. Linnaeus maybe therefore called the tree: *Theobroma cacao*, derived from the Greek 'food for the Gods'.

The Spanish court, after experimenting with the addition of sugar and vanilla liked the chocolate drink too. In 1828 the cocoa press was invented by the Dutchman van Houten, to extract much of the fat, and thus began the development of chocolate as we know it today.
In 1822 cocoa seeds were brought from Bahia, Brazil to the Portuguese island São Tome, off the West Coast of Africa. Cacao established well. Cocoa was introduced on other islands: Principe and Fernando Po. For a while these small islands were the world market leaders.

At the end of the 19th century cocoa was established in almost all West African countries; Ghana still was called Gold Coast. It was the Amelonado cocoa, with a fairly mild flavour, what the farmers were growing. In 1945 the quick growing Amazon was introduced from Trinidad. The flavour of Amazon was less good as that of Amelonado. Plant breeders tried to develop hybrids with a good cocoa flavour and a short period before setting pods.

Cocoa vs cacao
A rule of thumb is that when speaking of the whole tree the word 'cacao' is used. Cocoa (say 'coco') is used when speaking of crop, fruit, or manufactured products. (Are & Gwynne-Jones, 1974).

3 The water balance of cacao

In this chapter an overview of the aspects which deal with the waterbalance of crops wil be given. The theories about evapotranspiration will be explained in more detail in section 3.2.1. In section 3.2.2 will focus on tropical perennials and cocoa. In section 3.3 the root system of cocoa will be described.

3.1 The water balance at canopy level

A schematic representation of the water balance of a cocoa plantation is given in figure 3.1. The input of water in this system is gross precipitation; in other cases extra water is added by irrigation. Gross precipitation is intercepted by the canopy of the tree. The rain which reaches the soil is the sum of througfall and stemflow. The amount of rainfall that infiltrates into the soil is different from the amount above the canopy. If a cocoa plantation is situated on a hill, there will be some runoff.
Depending on soil characteristics, moisture will be available for plants for a longer or shorter period. Water that comes beneath rooting depth is lost as drainage.
The amount of water that is transpired by the cocoa trees depends on the potential evapotranspiration; the demand of water depends on environmental conditions. The actual transpiration is equal to, or less than the potential transpiration. When the bulk of water in the soil and/or the water uptake capacity of the roots are insufficient to satisfy the potential 'demand to water', they are the limiting factors.

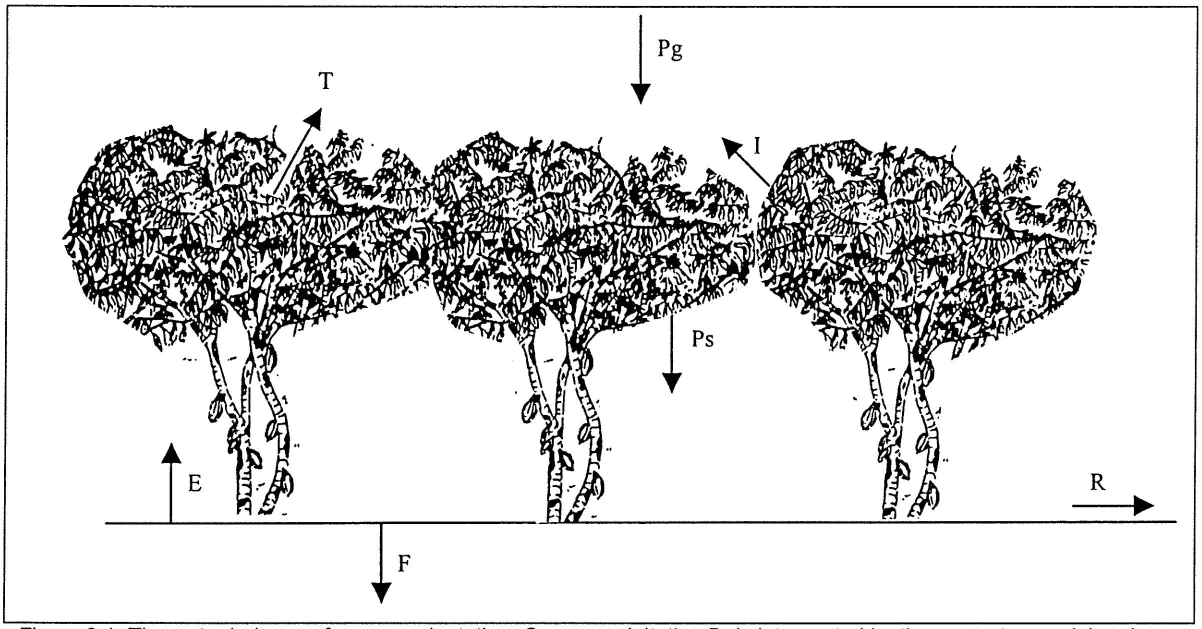


Figure 3.1: The water balance of a cocoa plantation. Gross precipitation P_g is intercepted by the cacao trees, giving rise to interception loss I. P_s is the rainfall reaching the soil; F is the infiltration rate, E evaporation from the soil; T.transpiration.

3.2.1 Theoretical backgrounds of evapotranspiration

The water balance of cocoa at canopy level consists of complex interactions between the soil water balance and the canopy energy balance and evapotranspiration. The term evapotranspiration includes the processes of evaporation of water in the soil into the air and of rain intercepted by the canopy, and the process of leaf transpiration. Evapotranspiration can be seen as an exchange of water for heat. Radiation provides the energy for transpiration.

Energy balance "sinks"
- sensible heat loss --> heat loss to surroundings
- latent heat loss --> transpiration
- metabolic storage --> photosynthesis, respiration process
- heat storage by the canopy
- soil heat flux into the ground

Before starting the calculation it is important to keep in mind that out of the short wave radiation, the photosynthetically active radiation (400-700 nm) drives photosynthesis. And total radiation drives transpiration. The total heat content of the air is the sum of the sensible heat content, dependent on temperature and of the latent heat content, dependant on vapour pressure.

Penman-Monteith

The Penman-Monteith combination equation which describes evapotranspiration of a whole canopy, is as follows (Monteith,1965):

$$\lambda E = \frac{\Delta(R_n - G) + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma^*}$$

λE is the latent heat needed for the transpiration and leaf evaporation (kW m^{-2});Δ is the slope of the vapour pressure curve which increases with temperature (kPa °C^{-1}); R_n is the net radiation flux at canopy surface (kWm^{-2});G is the soil heat flux (kWm^{-2}); ρ is the density of dry air (kg m^{-3}); c_p is the specific heat capacity of dry air (=1.013 kJ kg^{-1} °C^{-1}); e_s-e_a is the vapour pressure deficit, e_s is the saturated vapour pressure (kPa) and e_a the actual vapour pressure (kPa); r_a is the aerodynamic resistance (s m^{-1}). γ^* is an alternated psychrometric coefficient (kPa °C^{-1}), so that the formula describes canopy evapotranspiration.
When the leaf area index (LAI) is larger than 3.5, it can be assumed that G is zero.

Penman's original formula (Penman, 1948) describes evaporation from open water surfaces. γ depends on P, the atmospheric pressure (kPa), c_p (kJ kg^{-1} °C^{-1}) , ε the ratio of molecular weight of water vapour/dry air (= 0.622) and λ the latent heat (kJ kg^{-1}):

$$\gamma = \frac{c_p P}{\varepsilon \lambda}$$

Monteith (1965) modified γ by including water movement from the substomatal cavities to the leaf surface and from there across the boundary layer into the air.

$$\gamma^* = \gamma \left(1 + \frac{r_c}{r_a}\right)$$

This ratio of humidity increase and temperature decrease depends on the resistance of the evapotranspiration process. It is clear that an increase in r_c (the resistance of the canopy (s m^{-1})), leads to a decrease in transpiration loss. An increase in r_a (the aerodynamic resistance (s m^{-1}))

does not give such a clear change, because this parameter appears in both the nominator and the denominator of the Penman-Monteith combination equation.

To analyse the combination equation further we define an aerodynamic and a radiation driven part. We can write the Penman-Monteith combination equation so that it is easier to model.

$$ET_0 = ET_{rad} + ET_{aero}$$

ET_0 is the evapotranspiration of a crop canopy (mm d^{-1}), ET_{rad} is the radiation term, ET_{aero} the aerodynamic term. The following equation is obtained when all variables are written explicitly (van Kraalingen & Stol, 1997) (note that the γ used here is not γ^*):

$$ET_0 = \frac{1}{\lambda}\left(\frac{\Delta R_n}{\Delta + \gamma} + \frac{\gamma\ \lambda E_a}{\Delta + \gamma}\right)$$

λ is the latent heat (MJ kg^{-1}),);Δ is the slope of the vapour pressure curve (kPa °C^{-1}); R_n is the net radiation flux at canopy surface (kWm^{-2}); γ is the psychrometric coefficient (kPa °C^{-1}); E_a is the isothermal evaporation (mm d^{-1}) because it is the evaporation rate in the situation that the surface temperature is equal to the temperature at reference height.

Net radiation R_n can be written as:

$$R_n = (1-\alpha)R_s - R_{l,up} + R_{l,down}$$

The reflection coefficient α is called albedo, and different soil surfaces and crops have different values. The subscripts *s* and *l* refer to respectively short and long wave radiation. Often R_s has to be derived from sunlight duration measurements (van Kraalingen & Stol, 1997). $R_{l,up}$ can be described by the well known Stefan-Boltzman equation. Brunt (1932) developed a formula for the calculation of $R_{l,\ down}$..

Radersma & De Ridder (1996) and Wallace (1996) defined the equation as follows:

$$ET = \frac{\Delta R_n}{\lambda(\Delta + (1 + r_c / r_a))} + \frac{\rho c_p \delta / r_a}{(\Delta + (1 + r_c / r_a))}$$

The aerodynamic resistance (r_a) and the surface resistance of the canopy (r_c) are coupled in series. Studying the parts of this sum in more detail yields:

Aerodynamic resistance (r_a):
The aerodynamic resistance (r_a) of crops can be approximated with the following equation (Allen *et al.,* 1990), using wind speed profiles above the canopy and empirically determined averaged wind-profile parameters.

$$r_a = \frac{\{\ln[(z-d)/z_0]\}^2}{k^2 u_z}$$

In this equation z is the reference height (m), u_z is the wind speed at reference height z (ms^{-1}), d is the zero plane displacement (≈ 0.65 x crop height)(m), z_0 is the vegetation roughness parameter (≈ 0.13 x crop height)(m) and k is the von Karman constant (=0.41)(-). For a derivation of this constant, see Thornley & Johnson (1990).

Example 3.1 shows that an increase in crop height increases d and z_0 and decreases r_a. This means that a tree crop will generally have a lower aerodynamic resistance (r_a) and will transpire more easily. The reference height z is set to 10 in this example, to prevent a negative value for z-d.

	Height	z	u_z	K	d	z_{0t}	$r_{a,}$
Wheat	1.2	10	5	0.41	0.78	0.156	19.8
Cocoa	7	10	5	0.41	4.55	1.12	2.98

Example 3.2.1: Comparison between aerodynamic resistance of wheat and cocoa.

The isothermal evaporation E_a , as defined by van Kraalingen is proportional to water pressure deficit and wind speed. Each surface has a different wind function. For water and short grass these functions have been defined. Thom and Oliver (1977) proposed a formula for crops taller than grass. In these functions a reference height of 2 m is used. If the height of a crop is much taller than 2 m, this reference height does not make sense. The equation of Thom and Oliver (1997) can not be used for cocoa.

Surface resistance of the canopy (r_c):
The surface resistance of the canopy (r_c) depends on resistance of transpiration by the canopy, soil water evaporation and on zero-resistance to evaporation of intercepted rainwater. The canopy resistance can be seen as the parallel sum of these resistances (Jones,1983).

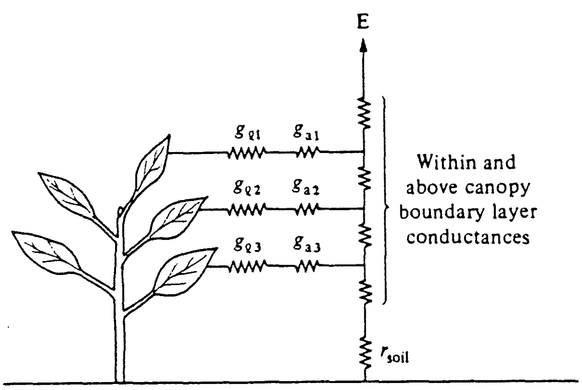


Figure 3.2.1 The pathways of water loss and the associated resistances for evaporation (E)(Jones, 1983).

McNaughton & Jarvis (1983) states that canopy resistance essentially depends on the sum of the stomatal resistances of the leaves, which means that the transpiration process has the greatest dependance on this resistance.

$$r_c = \left(\sum_i \frac{l_i}{r_{st,i}} \right)^{-1}$$

Canopy resistance (r_c) in sm^{-1}, l_l is the leaf area index on a specific height, $r_{st,l}$ represents the resistance of the stomata.

In a FAO report (Allen *et al.,* 1990) the crop canopy resistance was described as:

$$r_c = r_l / (0.5 * LAI)$$

When data are lacking, there is the simple approach of Kelliher *et al.* (1995). This compares minimum resistances at leaf and canopy scale, for non-stressed crops at LAI of more than 3.5. They found that the canopy resistance is three times lower than the minimum leaf resistance.

3.2.2 Focus on cacao

In general tree crops have a higher level of transpiration than annual crops. In tree crops the leaves are present throughout the whole year, whereas annuals leave the soil bare for some time of the year. Another reason for the higher rate of evapotranspiration is that the aerodynamic resistance of tree crops is smaller. The aerodynamic resistance decreases with height (see example 3.2.1). Since r_a and r_c are coupled in series ($r_{total} = r_a + r_s$), r_a is relatively more important for annuals. In perennial tree crops r_c may be of greater importance. (Jones, 1983)

Radersma & De Ridder (1996) compared the crop transpiration of crops as cocoa, oil palm, rice and maize. Under increasing moisture stress, causing stomata to close, transpiration decreased. The stomatal resistance of the tree crops increased more than the stomatal resistance of annuals under comparable water stress conditions. Tree crops seemed to suffer more from water stress. In practice this difference will be levelled out, because tall crops have deeper root system and thus exploit larger soil volumes. Tall crops will suffer later from water stress in drying soil.

In the West African situation irradiance is high, so the first term of the denominator is high (see equation of Van Kraalingen, p24). Windspeed is low, so relatively low values for the second term will be calculated.

3.3 Root distribution in the soil.

As already mentioned in chapter 2 the root system of cacao is characterised by a deep tap root and dense mat of fine roots in the upper soil layer. Only the finest roots (diameter < 2 mm) of the fine roots are able to take up water (pers. com. Goudriaan). The tap root, that anchores the tree in the soil and the bigger lateral roots are suberised. The distribution of the fine root biomass determines the quantity of water that can be taken up from a soil layer.
In this section two processes will be described:
1) The growth of the taproot,
2) The growth of the lateral roots within the soil.

Taproot
The depth from where water can be taken up, depends on the length of the taproot. The taproot itself does not take up water, but the fine roots which branch from it, do. At the end of the taproot some lateral roots appear, which can be important for the uptake of water in dry periods.

The length of the taproot depends on the age of the cocoa, assuming that the soil characteristics are not limiting. The taproot will reach 80 cm within five years, and under good conditions the taproot will penetrate deeper soil layers, up until 1.50 m (SOFRECO, 1991). Depths over 2 m have been found (Wessel, 1971a). However it is often not clear whether or not an author includes the deep reaching lateral roots in the definition of the taproot.

Age	4 m	16 m	2 year	3 year	6 year	11 year	14 year
Length tap root (cm)	30	40	51	61	70	95	100
∅ tap root (cm)	0.85	3.2	3.9	4.9	7.5	10.0	10.5
Ratio length: ∅	35.3	12.5	13.1	12.4	9.3	9.5	9.5

Table 3.3.1: Length and diameter taproot, after Himme (1959).

Data from Himme (1959) indicate the length of the taproot has a negative exponential relation with age (Appendix 3e). By fitting the derivative function, the growth rate of the taproot can be found. Growth has a negative exponential distribution with age (figure 3.3.1).
Himme (1959) also collected data for the diameter on the taproot (DTRT) at collar, where the root grows into a stem. These data are not used in the same way as for the length of the taproot, because of the relatively constant ratio between length and diameter (see table 3.3.1).

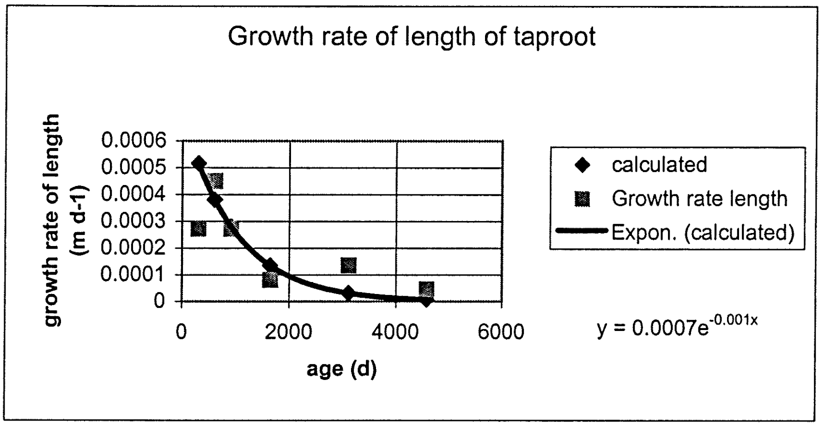


Figure 3.3.1: Taproot length growth rate (Himme, 1959).

Teoh *et al.*(1986) state that more than 70% of cocoa trees in his experiments have a bifurcated taproot. He studied cocoa trees on coastal clays in Malaysia. Himme (1959) described the taproot as cilindrical for the first 10-20 cm, and as conical and forked deeper under the surface. Himme collected his data in Belgian Congo. Kummerow *et al.* (1981) calculated the biomass of the taproot by assuming that it is a cone.

Fine roots

Kummerow *et al.* (1982) stated that 90 % of the roots is located in the upper 10 cm of the soil. He described a site in Brazil. However Cadima & Coral (1972) found out that 90 % of the rootlets is located in the first 30 cm of the soil. The remaining 10% were distributed with decreasing density over the deeper soil layers. Also Teoh *et al.* (1986) found that almost 90% of the roots grow in the first 30 cm of the soil. Wood (1971) writes in general that most of the roots appear within the upper 20 cm of the soil. Thong & Ng (1978) found a contrasting root distribution in Malaysia on the coastal clays. The distribution of lateral roots with respect to the soil depth was 38, 31 and 31 % for soil depths of 0-30 cm, 30-60 cm, 60-90 cm. Because this root distribution differs from the situation as most often found in West Africa these results were not taken into consideration.

Kummerow *et al.*(1981) collected data in an experiment with 11-year-old cocoa trees in Brazil. He defined four classes of diameters. The second and third column contain the data of the finest roots. Kummerow *et al.* (1981) took 100 samples of a depth of 0-10 cm.

Root ∅ (mm)	< 1	1 - 2	2 - 5	> 5	Total
Dry weight (g/m2)	33	43	78	230	384
σ	1.7	3.6	8.3	28.7	
Length (m/m2)	1201	114	28	18	1361
σ	58	7	3	2	

Tabel 3.3.2: Dry weight and length of different root classes in a 0-10 cm soil profile. σ is the standard deviation. After Kummerow *et al.* (1981).

Kummerow *et al.*(1981) estimated the fine root biomass of the whole soil profile to be 768 g m-2. Including the weight of tap root and suberised laterals, the total weight of the roots is 1038 g m-2. Teoh et al. (1986) measured a fine root biomass of 755 g m^{-2} for a soil depth of 0-90 cm for 8 year old cocoa trees in Malaysia. For 11 year old coca trees he found a fine root biomass of 561 g m^{-2} , but the root system of these plants could be influenced by the height of the water table. The fine root biomass in the experiments of Thong & Ng (1978) is a factor five less than in the experiments of Teoh *et al.* (1986) and Kummerow *et al.* (1981). Thong & Ng (1978) found only 57 g m^{-2} for 6-year-old trees. In comparison, Teoh *et al.* (1986) found 283 g m^{-2} for 6-year-old trees. The data of Kummerow *et al.* (1981) and Teoh *et al.* (1986) are used to initialise the model.

Age (years)	DM fine roots kg/ha
6	2830
8	7550
11	5610
15	13910

Table 3.3.3: Dry weight (g/m2) of the fine root system of cocoa of different ages. After Teoh *et al.* (1986)

The distribution of fine roots can be approximated in a function of exponential decrease:

$$W = W_0 * e^{-kz}$$

W is the fine root biomass (kg ha^{-1}), W_0 is the maximum biomass (kg ha^{-1}), k is the relative decrease of the roots by increasing depth (m-1), and z is the soil depth (m). The data of Kummerow *et al.*(1981) are fitted visually (see figure 3.3.2).

Class(cm)	Mean depth (m)	DM fine roots per class (kg/ha)	DM fine roots per volume (kg/ha/cm)
0 - 5	0.025	2460	492
5 - 10	0.075	1280	256
10 - 15	0.125	970	194
15 - 30	0.225	1030	68
30 –120	0.75	1150	13
Total		6890	

Table 3.3.4: after Kummerow *et al.* (1981) and Cadima & Coral (1972)

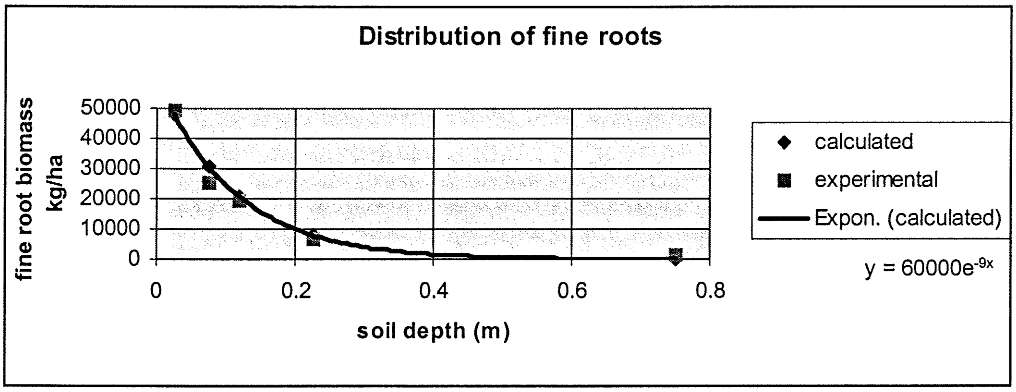


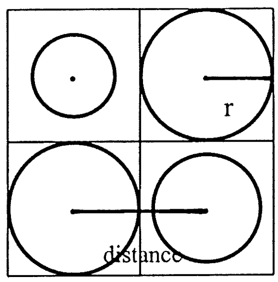
Figure 3.3.2: Distribution of fine roots: exponential decrease (Kummerow *et al.*, 1981)

The cacao tree has a specific rootlet characteristic: In the mineral soil layer the distal ends of lateral roots branch into bundles of elongated and sparsely branched fine roots and in the litter layer into clusters of abundantly branched roots (Kummerow *et al.*, 1981). The root biomass therefore is not evenly distributed (see figures of Himme, 1959). The finest roots (∅<1mm) have a mean diameter of 0.22 mm. Thirty-three grams of the finest roots extended over a distance of 1200m, the specific root length is 36 m root g-1 root. For the second class (1-2 mm) the specific root length is 3 m root g-1 root. Kummerow *et al.* (1981) estimated that the mean distance between roots in the upper 3 cm is 2-3 mm. That should assure an efficient retention of nutrients in the rooting zone.

Calculating the distance between all roots with a diameter smaller then 2 mm in a soil depth of 10 cm, as in the experiments of Kummerow *et al.* (1981) we find that the mean distance between the finest roots is about 10 mm.

Box 3.3.1: calculating root density

1315 m root per square meter soil area (A)
1315 cylinders of 1 m length
soil depth = 0.1 m
soil area horizontal (B) :1m x 0.1m = 0.1 m2,
contains 1315 planes
The area of 1 plane is:
0.1 / 1315 = 0.000076 m2 = 76 mm2
The length of one plane (C) is $(76)^{0.5}$ = 8.48mm
The mean distance between roots,
from centre to centre is about 10 mm.



Root growth dynamics

Growth of roots

Kummerow's experiments (Kummerow *et al,* 1982) showed that the fine root biomass was relatively stable over a period of six months. In contrast the number of growing rooting tips per unit soil volume changed significantly. We can only speculate that the turnover of fine roots in warm and moist conditions is very high.

The changes in the growth activity of the fine roots seems not to be correlated with climatic conditions (Kummerow *et al.*, 1982). Kummerow *et al.* (1982) found a negative correlation between flushing in January and the activity of the root system. This might indicate that the growth of roots is determined by the quantity of carbohydrate reserves that is available.

4 Model

4.1 Some principles of the Fortran Simulation Environment (FSE)

The actual model is programmed as a separate subroutine. It is linked to the FSE-driver. This driver takes care of task sequencing, checks weather data and controls time events and handles data in- and output.

One of the advantages of FSE is that the scientific part of the model is separated from the computational overhead. Input data reading, output data writing, checks on weather data and other functions are placed in utility routines, the so called TTUTIL utility library. The utility routines have a clearly defined task, but their FORTRAN code can be rather complex. This complex functionality is hidden in this system, because the modeller only uses the calls to the utility routines.

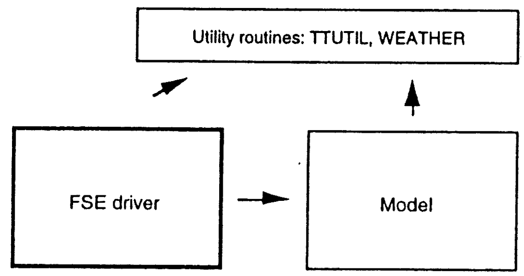


Figure 4.1.1: Simplified structure of FSE (Van Kraalingen, 1995).

Order of execution

FSE adopted the Euler method for integration, because it makes the programme structure less complicated. To ensure that the results of the simulation are correct, different types of calculations should be strictly separated. At the start of the programme all states should be initialised, then the rates are to be updated. The calculations of the rates and state variables cannot be mixed during a time step, the parts in which these calculations are executed are rigorously separated.

This theory of continuous simulation using Euler integration is also called: The task-controlled execution concept. It is implemented in FSE using an integer variable `ITASK` that can have four different values, indicating the section of execution: `ITASK1`=initialisation, `ITASK2`=rate calculation, `ITASK3`=integration, `ITASK4`= terminal. Most subroutines are structured according to this principle.

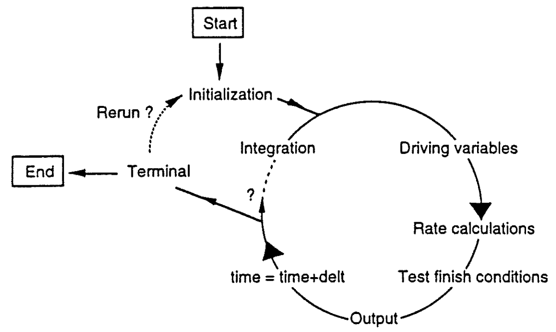


Figure 4.1.2: The order in which calculations are executed (after van Kraalingen, 1995).

Since the states have been initialised in the initialisation section, it is permissible to compute rates of change directly after initialisation (van Kraalingen, 1995).

Initialisation section

As mentioned earlier, in this section parameters have to be given a value and states have to be initiated.

This can simply be done by a statement such as `RGR=0.1`. But parameter values and initial states can also be read from external data files. These values are extracted by subroutines from the TTUTIL library, whose names all begin with RD.... . The statement `CALL RDSREA ('WLVI' WLVI)` requests the subroutine `RDSREA` to `ReaD` the `Single` `REAl` value from the data file and assigning it to the variable `WLVI`.

For more examples and an overview of the available input routines in the TTUTIL library, see van Kraalingen (1995).

Output of simulation results

To avoid communication problems between subroutines and the main model, output is given by the subroutines separately. It is also possible to write output from different subroutines into one output file in the form of tables. The use of a special set of subroutines, the OUT routines of TTUTIL simplifies the generation of output files. The routine `OUTDAT` for output of single real values, `OUTARR` for one-dimensional arrays of real variables. For more detailed explanation, see van Kraalingen (1995).

4.2 About CASE2

4.2.1 General structure

The model for cocoa growth and production, CASE2 (CAcao Simulation Environment production level 1 and 2) was implemented with the Fortran Simulation Environment (FSE) (Van Kraalingen, 1995). The model CASE2 consists of a main program which calls the FSE driver (fse.for). General principles and tasks of the driver are explained in section 4.1.

The FSE driver calls the subroutine models (model2.for) which uses three modules: a plant module, an evapotranspiration module and a soil water balance module.
The plant module is also called CASE2. It is the cacao version of SUCROS. It simulates light interception of the shade crop and of cocoa, canopy photosynthesis, cocoa crop growth, development, water uptake and transpiration (Gerritsma, 1995).
SETPMD, the evapotranspiration module used is based on the equation of Penman-Monteith. The subroutine SETPMD calculates two variables, needed to calculate the potential evapotranspiration. The potential evapotranspiration itself is calculated in CASE2.
The soil water balance module simulates the soil water content, moisture distribution, soil evaporation and drainage. The subroutine DRSAHE is used. For details see van Kraalingen (1994).

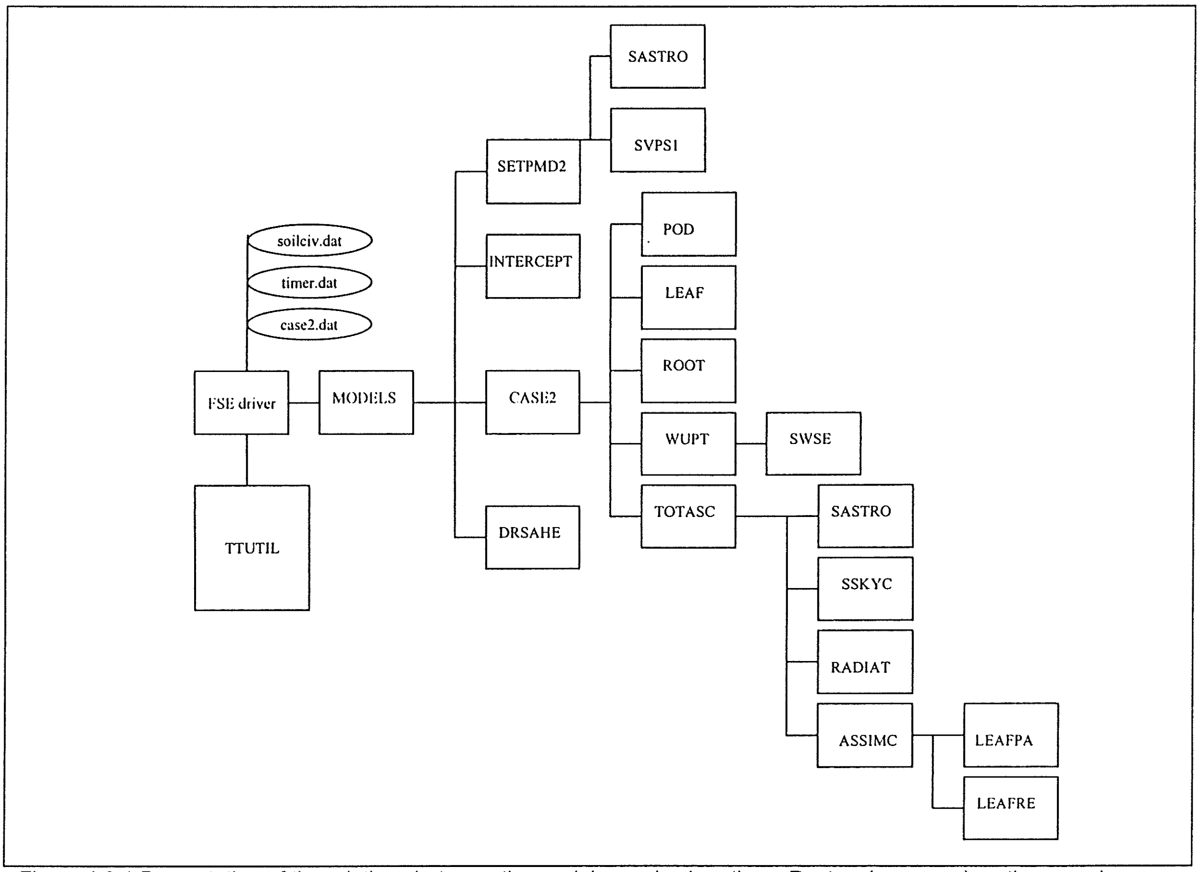


Figure 4.2.1 Presentation of the relations between the modules and subroutines. Rectangles are subroutines; ovals are data files. TTUTIL is the FORTRAN utility library.

4.2.2 Differences between version 1.1 and 1.2

One of the goals of this thesis is to improve the simulation model CASE2 for water limited situations. In view of this the root system of cocoa has been studied in detail, because the roots are responsible for the uptake of water. Further, evapotranspiration and different ways to model evapotranspiration have been studied.

Root growth and distribution
Root growth and root distribution are modelled differently in version 1.2 than in version 1.1. In CASE2 version 1.1 the roots are modelled like in SUCROS. The basic assumption in SUCROS is that the length of the roots varies enormously without much relation to their weight (van Laar *et al.*, 1997). In SUCROS two variables are important:
- The state ZRT, the depth from which the crop effectively extracts water.
- The effective root length ERLB is determined by the root activity coefficient. This coefficient varies between one and zero and is inversely related to the relative amount of water in a soil compartment.

There is one layer in which root growth takes place.
These two variables do not give much flexibility to describe specific root characteristics. The distribution of roots in the soil can not be modelled. Interactions between roots of different species can not be modelled easily.

In version 1.2 the root distribution and growth are modelled more explicitly. The root system is not seen as a black box with root activity coefficients, determining the water uptake. Only a few data were available, but enough to get an indication about the most important variables needed.
- The length of the taproot LTRT at a certain age. The length of the taproot determines the depth from where water can be taken up, the rooting zone. The potential growth of the taproot is still a first order process. The potential growth is calculated by an empirical function of exponential decrease (Himme, 1959).
- The distribution of the fine roots in the soil WFRT. The basic assumption in the SUCROS was abandoned. The length and root area of the roots able to take up water can be calculated from the biomass of the fine roots. The decrease of the fine roots by soil depth and the water uptake capacity are described in a function of negative decrease. The root activity coefficient is not needed. A switch for soil moisture determines whether or not growth can take place. The ratio between lateral roots (∅>2mm) not able to take up water and lateral roots (∅<2mm) able to take up water is constant. The specific root length and mean diameter of the roots able to take up water are known.

Evapotranspiration
In version 1.1 for the calculation of the evapotranspiration, the subroutine SETPMD (Subroutine EvapoTranspiration PenMan Daily)(Van Kraalingen & Stol, 1997) was used. This subroutine calculates reference evapotranspiration in a manner similar to Penman (1948). Calculations can be carried out for three types of surfaces: water, wet soil and short grass. In version 1.1 the evapotranspiration of the cocoa canopy is modelled like a short grass surface.

The wind functions for the three surfaces differ. For crops taller than grass other wind functions have been mentioned, e.g the formula of Thom & Oliver (1977). The problem is that the formulas proposed, are not applicable to crops taller than 2 m. Cocoa can reach a height up to 10 m.

The Penman Monteith equation as referrred to in a FAO report about crop water requirements (Allen *et al.,* 1990), is the base of the evapotranspiration module of version 1.2 (see paragraph 3.2.1). The parameters aerodynamic and canopy resistance (r_a respectively r_c) are important. In this equation the wind function is not used explicitly. The aerodynamic resistance is influenced by wind speed. For West African conditions wind speed can be set to 1.5 m/s at canopy height (Radersma & De Ridder, 1996). The canopy resistance is estimated by using the simple approach of Kelliher *et al.* (1995). They found that the canopy resistance is as much as three times lower than the leaf resistance.
Another advantage of the equation of Allen *et al.* (1990) is that γ^* is implemented. γ^* is used in plant models. The difference between γ and γ^* is that water movement from the substomatal cavities to the leaf surface and from there into the air is taken into account.
With this equation the evaporation of all crops, also crops taller than two metres can be calculated.

4.3 Model description

In this thesis subroutine ROOT was the starting-point, so in the model description it is explained first (4.3.1). When implementing ROOT in the system we had to change subroutine CASE2. The changes in this subroutine are described secondly (4.3.2). Third the new routine INTERCEPT is explained (4.3.4). The changes in subroutine WUPT are described (4.3.3) fourth. In section 4.3.4 the changed evapotranspiration module is described.

4.3.1. subroutine root

The general purpose of this subroutine is to calculate the root area active in extracting water from of the soil.

Initialisation

In the initialisation section, ITASK=1, the plant parameters and tables are read from the plant data file (case2.dat). All variables and arrays are set to zero.
The taproot will be initialised with the initial length (LTRTI), read from the length table (LTRTB), with the lint function (LINT) for a given age (AGE). The diameter is described as 0.10 x length (see table 3.3.1) The weight of the taproot for a single tree is calculated by multiplying the volume of the root by the specific mass. The volume of the root is assumed to be a cone (1/3 x basis x height) (Kummerow *et al*, 1982). The volumetric mass (SW) of wood in general is 0.92 (Verkerk, *et al.,* 1992). It is a mean value calculated from several species. Boyer (1973) found for the wood of cocoa a value of 0.34, by averaging results of 18 cocoa trees. Daymond found a value of 0.5 for cocoa grown in Brazil (Gerritsma, pers. com.)
The weight of the taproot of a single tree multiplied by the number of plants per hectare (NPL) gives the weight of the taproots per hectare (WTRT).

```
LTRTI = LINT (LTRTB, LTRTMN, AGE)
LTRT = LTRTI
DTRT = 0.10 * LTRTI
WTRT = PI*(DTRT/2.)**2.)/3. * LTRT * SW * NPL
```

The length of the taproot (LTRT) determines the depth of where water can be taken up (CUMTKL), the rooting zone. So the length of the taproot determines how many soil layers of known thickness (NLA) are actually used in the plant module. NLA must be smaller or equal to the number of defined soil layers of the soil profile, NL. Note that NLA and CUMTKL are already set to zero.

```
* Calculating the number of rooted soil layers, acting in the plant
module.
      DO I1 = 1, NL
            IF (LTRT.GT.CUMTKL) THEN
               NLA = NLA + 1
               CUMTKL = CUMTKL + TKL(I1)
            ELSE
               NLA = NLA
            ENDIF
      END DO
```

In the model it is assumed that the fine roots are evenly distributed within each soil layer. We assume too that 90 % of the roots is located in the first 20 cm (see table 3.3.4).
The distribution of the fine roots can be approximated in an exponentially decreasing function:

$$W = W_{max} * e^{-kz} \qquad \text{Eq. 4.3.1}$$

W is the biomass density of fine roots per ha (kg ha-1 m-1), W_{max} is the biomass density of the fine roots at z = 0 (kg ha-1 m-1), z is the soil depth (m). k is the characteristic depth at which the root biomass has decreased with 1/e (m-1). In this case k = 9.0 (see figure 3.3.2).

The maximum fine root biomass (`WMAX`) (kg ha-1 m-1) in the soil depends on age (x). The table (`WMAXTB`) is derived after Kummerow *et al.*(1981).

```
WMAX = LINT (WMAXTB, WMAXMN, AGE)
```

The weight of the fine roots will be distributed in classes, depending on soil depth. The weight of the fine roots will be classified in array `WFRT(I1)`, in as many parts as actual soil layers (`NLA`) are defined by the length of the taproot.
To initialise the array we need the integral of equation 4.3.1.

$$\int W\,dz = W_{max} * (-1/k) * \exp(-k*z)$$

Using this integral we find from table 3.3.4 that W_{max} is 66000 (kg ha-1 m-1, note that W_{max} does not have the same dimension as $\int W$) and k= 9 (m-1). To distribute the fine roots in classes, the borders of the soil layer have to be filled in (see figure 4.3.1).

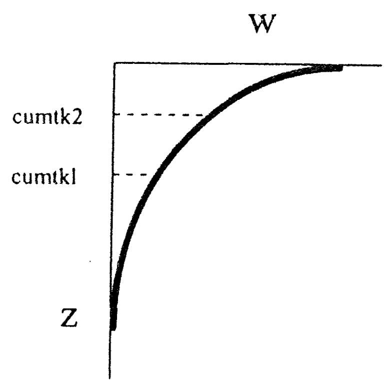


Figure 4.3.1: Initialising the fine root array.

```
*       Initialise array of fine roots.

        CUMTKL = 0.

        DO I1=1, NLA
              CUMTK2 = CUMTKL
              CUMTKL = CUMTKL + TKL(I1)
              WFRTI(I1)= WMAX * (-1/9.0) * EXP(-9.0*CUMTKL) -
     &                 WMAX * (-1/9.0) * EXP(-9.0*CUMTK2)
              WFRT(I1)=WFRTI(I1)
              WTFRT = WTFRT + WFRTI(I1)
        END DO
```

At the end of `ITASK=1` the total root weight (`WRT`) is calculated.

```
WRT = WTRT + WTFRT
```

Dynamic section

In the rate calculation section, `ITASK=2`, there is a check on the length of the taproot. When the taproot grows, once it will penetrate a new soil layer (in computer terms: `NLA` increases with one). A new class of fine roots will be 'used'. The array `WFRT(I1)` is over-dimensioned, because the dimension of the array is defined as `NLXM`. `NLXM` is a parameter and should always be taken larger than `NLA`. In the array `WFRT` a new part will be used, before this moment it was empty; it had value zero.

The new class of fine roots, `WFRT(NLA)` has to be initialised. At this discontinuity, the 'replace method' will be used (Leffelaar, 1993), directly when the check on the length of the taproot takes place.

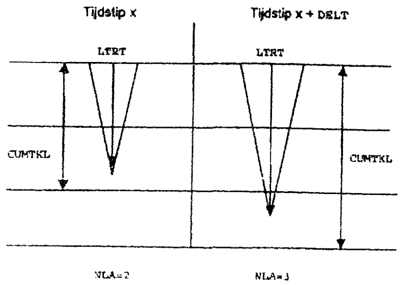


Figure 4.3.2: The growth of the taproot, as defined in the model.

```
*       Number of soil layers in project
      DO I1 = NLA, NL
            IF (LTRT.GT.CUMTKL) THEN
              NLA = NLA + 1
              CUMTKL = CUMTKL + TKL(I1)
              WFRT(NLA)= WFRTI
            ELSE
              NLA = NLA
          ENDIF
      END DO
      IF (NLA.LT.NL) CALL FATALERR ('ROOT', 'NLA is smaller than NL')
```

When the taproot reaches a new soil layer, that new soil layer will be initialised for its entire depth. Even when the taproot cuts the new layer for one millimeter, the whole layer can be used for water uptake by the fine roots. When the taproot grows further in this layer, no new initialisation takes place, like Sucros97 (van Laar *et al.*, 1997).

When growth of roots occurs, the actual soil moisture level (`WCLQT`) must be above wilting point (`WCWPX`). `WSERT` is a soil moisture parameter, a switch that indicates whether the soil moisture level is above wilting point, or not. If `WSERT` is one, root growth can take place.

```
* Calculating WSERT
      DO I1=1, NLA
          WSERT(I1) = 1.
          IF (WCLQT(I1).LT.WCWPX(I1)) THEN
              WSERT(I1) = 0.
          END IF
      END DO
```

The growth rates of the taproot and the fine roots are not calculated in this subroutine, but in the `ITASK=2` section of subroutine case2. In case2 the partitioning of the reserves takes place.

Because this partitioning determines the growth rates of the different organs of the plant, the growth rate of taproot and fine roots is not calculated in subroutine root.

Only a fraction of the fine roots (FFRT) is able to take up water. Roots with a diameter less than 2 mm are able to take up water. 20 % of the fine roots have a diameter less then 2 mm (Kummerow *et al.*, 1981). The weight of the roots able to take up water (WWURT) is calculated by multiplying the fraction of finest roots (FFRT) with the weight of the fine roots (WFRT).

```
WWURT(I1) = FFRT * WFRT(I1)
```

Water uptake is proportional to the root surface area. In the model we define two classes: roots with diameter less than 1 mm and roots with a diameter between 1-2 mm.

Knowing two parameters, specific root length (SPRTL) and diameter (DIAM), the length (LWURT) and so area (AWURT) of the roots able to take up water, can be calculated. The specific root length for the finest class is 36 m/g, and for the remainder class 3 m/g (Kummerow *et al.*, 1981). Kummerow *et al.* (1981) found an averaged root diameter of 0.22 mm for the finest root class. We assume that the mean diameter of the second class is 1.5 mm.

Box 4.3.1 Calculation of rootlet surface able to take up water

biomass -->	length of rootlet --> multiply with specific root length (Kummerow, 1981).	rootlet surface $2\pi r$*root length (Kummerow, 1981).

```
LWURT=0.
      DO I1=1,NLA
          LWURT1(I1) = 0.5 * WWURT(I1) * SPRTL1
          LWURT2(I1) = 0.5 * WWURT(I1) * SPRTL2
          LWURT = LWURT + LWURT1(I1) + LWURT2(I1)
      END DO

      AWURTT=0.
      DO I1=1, NLA
          AWURT(I1) = (PI*DIAM1)*LWURT1(I1)+
     &                           (PI*DIAM2)*LWURT2(I1)
          AWURTT = AWURTT + AWURT(I1)
      END DO
```

When growth occurs, WFRT increases, and therefore WWURT. What has not been made explicitly here is a switch from roots of WWURT to WFRT. The lateral roots, able to extract water, grow and suberise. Then they are not able to take up water for some more time. In computer terms: they are no longer in the class of WWURT. The ratio between WFRT and WWURT does not change, it is a constant (FFRT). Growth in diameter of the finest roots (WWURT) is not important.

In the integration section, ITASK=3 the biomass of the fine roots and the taproot are calculated.

```
      WTFRT = 0.
      DO I1=1, NLA
           WFRT(I1) = INTGRL (WFRT(I1), GFRT(I1)-DFRT(I1), DELT)
           WTFRT =  WTFRT + WFRT(I1)
```

```
END DO

WTRT = INTGRL (WTRT, GTRT, DELT)

WRT = WTRT+WTFRT
```

4.3.2 subroutine case2

This subroutine is the cacao version of SUCROS, to calculate growth in situations of water limited production. In this paragraph not all equations of the subroutine are explained . Only the changes made in this thesis are described. Mostly they deal with partitioning and growth, therefore the `ITASK=2` section is most important and will be fully discussed. For the description of subroutine `CASE2`, version 1, see Gerritsma (1995), chapter 6.

In section `ITASK=2` first there are some statements about age and weather. Secondly the subroutines `ROOT` ,`WUPT` and `TOTASC` are called.

Maintenance respiration
After the carbohydrate production calculation `(GPHOT)`, maintenance respiration for the whole tree `(MAINTS)` will be calculated. All plant tissues have different maintenance coefficients (kg CH2O ha-1 d-1) `(MAINRT, MAINLV, ...)`. It is assumed that the taproot has a maintenance coefficient equal to wood. The maintenance respiration for each tissue can be calculated by multiplying the maintenance coefficient by the weight of the tissue. Only the living tissue needs to be taken into account. For the calculation of the maintenance respiration of trunk, branches and taproot the moribunt heartwood tissue `(FRSUPW)` can be excluded.
Higher temperatures increase the costs of maintenance respiration, because of increased turnover. The effect of temperature on maintenance respiration `(TEFF)` is simulated assuming a doubling of the maintenance respiration at every 10 °C increase from the reference temperature (Goudriaan & van Laar, 1994). Assimilated carbohydrates in excess of the maintenance costs are used for the growth of the reserve pool `(GRES)`.

```
*     Maintenance
      MAINTS = MAINRT*WTFRT + MAINRT*WTRT*(1-FRSUPW)+
   &           MAINWD*WWD*(1-FRSUPW)+ MAINLV*WLVG +MAINPD*WPD
      TEFF   = Q10**((TMAV - TREF)/10.)
      MAINT  = MAINTS * TEFF
      GRES   = GPHOT - MAINT
```

Dry matter partitioning
Partitioning of reserves over the various plant organs is described by fixed distribution factors, defined as a function of crop age. The partitioning occurs in two steps. Dry matter is first partitioned in an above and below ground fraction, cq. shoot `(FSH)` and root `(FRT)` fraction. The root-shoot ratio is taken constant over the time, 1:4.
Secondly the two fractions will be partitioned further. The above ground fraction will be partitioned in a leaf `(FLV)`, wood `(FWD)` and pod `(WPD)` fraction (see figure 4.3.2). The below ground dry matter is partitioned between fine roots `(FRTF)` and taproot `(TRTF)`. The ratio 4:1 between these fractions `(PFRT:PTRT)` is based on Kummerow *et al.* (1982).

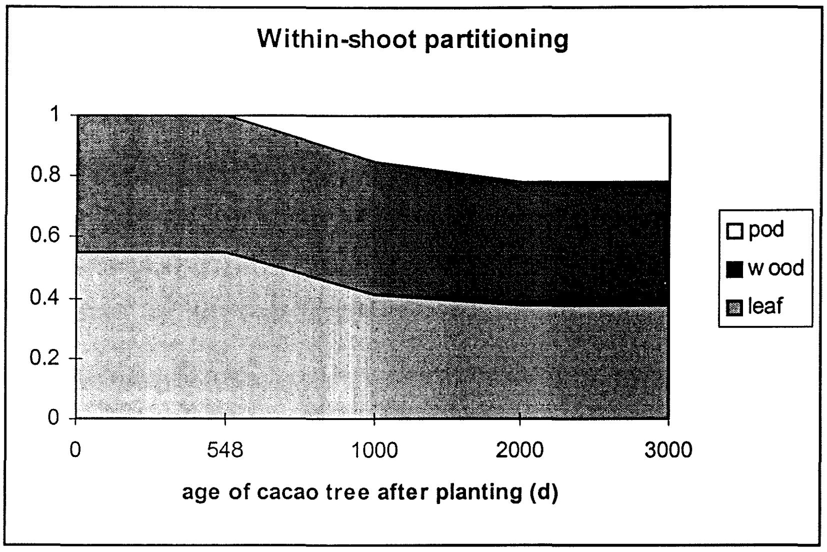


Figure 4.3.2: Diagram of partitioning within the shoot. The root-shoot ratio is kept constant.

```
*       Dry matter partitioning
        FSH     = LINT (FSHTB, IFSHN, AGE)
        FLV     = LINT (FLVTB, IFLVN, AGE)
        FWD     = LINT (FWDTB, IFWDN, AGE)
        FPD     = LINT (FPDTB, IFPDN, AGE)
        FRT     = 1. - FSH
        FRTF    = PFRT * FRT
        TRTF    = PTRT * FRT
```

The overall value of assimilate requirement for the conversion of carbohydrates into dry matter (ASRQ) (kg CH2O kg-1 DM) for the crop as a whole is calculated as the weighted mean of the ASRQ's for the different plant organs. The taproot assimilate requirement (ASRQTRT) is considered as being wood. Because wood contains much lignine, the taproot has a higher ASRQ-value than the fine roots.

```
*         Assimilate requirements for growth
          ASRQ    = FSH * (ASRQWD*FWD + ASRQLV*FLV + ASRQPD*FPD) +
&                      ASRQFRT*FRTF + ASRQTRT*TRTF
```

Growth takes only place when the amount of carbohydrate reserves exceeds some base level (MINRES) and the daily maintenance requirements (MAINT). The minimum reserve level depends on the biomass and the minimum concentration of sugar. The carbohydrates in excess of MINRES divided by TAU, are used for growth (DRES). TAU is a time coefficient; it delays the use of reserves, to prevent the tree from exhaustion of reserves. The dry matter growth rate is represented by GTW.

```
*         Growth takes only place when the reserves exceed the minimum
*         reserve concentration plus maintenance requirements
          IF (WRES .GT. MAINT*DELT + MINRES) THEN
            DRES = (WRES - MINRES)/TAU
            GTW  = DRES / ASRQ
          ELSE
            DRES = 0.
            GTW  = 0.
          ENDIF
```

Growth of the individual above ground plant organs (GWD, GLV, ...) is based on the dry matter growth rate (GTW), the root:shoot partitioning (FSH) and partitioning of shoot dry matter over the above ground plant organs (FWD, FLV,...).

```
*       Growth of plant organs (and translocation)
        GWD    = FWD * FSH * GTW
        GLV    = FLV * FSH * GTW
        GPD    = FPD * FSH * GTW
```

The growth of leaves and pods is further detailed in the subroutines LEAF and POD. In these subroutines dry matter growth is divided over age classes which keep track of leaf and pod development as well. Leaf senescence (DLV) and yield (YIELD) are the output of the respective subroutines.

Taproot growth
The growth of the roots (GRT) depends on the fraction of roots (FRT) and the dry matter growth (GTW).
The growth of the taproot (GTRT), is based on the dry matter growth rate (GTW), the root:shoot partitioning (FSH), partitioning of root dry matter over the fine roots and taproot (FRTF, TRTF) and a factor (WSERT) which reduces root growth in case of drought. The growth of the taproot (GTRT) source limited.

```
GRT  = FRT * GTW
GTRT = TRTF * GTW * WSERT(NLA)
```

The growth rate of the taproot (GTRT) (kg ha-1 d-1) will be compared with a potential growth rate (PGTRT) (kg ha-1 d-1). The potential growth rate (PGTRT) depends on the age of the cocoa tree, because the length (PGLTRT) and diameter growth depends on age. The potential growth rate (PGTRT) is sink limited. The potential growth rate (PGLTRT) is derived from the data of Himme (1959). The diameter growth is estimated as 0.10 of the length growth (see table 3.3.1).
Note that 'potential' is meant as maximum growth at certain age and not as 'potential' in an agro-ecological view. The fact is that the data are collected in a limiting environment, so the potential growth data used here are an underestimation of what we normally understand for potential growth.

To calculate the potential growth rate (PGTRT) first the length of the taproot (LTRT) must be calculated. The weight of the taproot is known, so it is possible to calculate LTRT.

Box 4.3.1 Calculation of length of the taproot

Weight of taproot per ha	= 1/3 x base	x height	x specific mass	x number of trees	
WTRT	= 1/3 x π x r^2	x LTRT	x SW	x NPL	

r = LTRT/ (10 x 2)
WTRT = SW x NPL x π x (1/1200) x $LTRT^3$
LTRT = ((WTRT x 1200) / (SW x NPL x π))$^{1/3}$

```
QUOTIENT = (WTRT * 1200)/(SW * NPL * PI)
LTRT     =  QUOTIENT**0.3333
```

Using the derivative function of WTRT, the growth rate of the taproot mass per length (GMASS) (kg ha-1 m-1) can be calculated. The potential growth rate of length per time (PGLTRT) (m d-1) is known by a function fitted by the data of Himme (1959) (see figure 3.3.1). Multiplying these two variables the potential growth rate of the taproot (PGTRT) (kg ha-1 d-1) is calculated.

Box 4.3.2. Derivative function of WTRT

$$WTRT = SW \times NPL \times \pi \times (1/1200) \times LTRT^3$$
$$WTRT' = SW \times NPL \times \pi \times (1/1200) \times 3 \times LTRT^2$$
$$WTRT' = SW \times NPL \times \pi \times (1/400) \times LTRT^2$$

```
* Growth rate of taproot mass, per length (kg/ha/m)
      GMASS = SW * NPL * PI * (LTRT**2)/400

* Growth rate of length per time (m/d)
      PGLTRT = 0.0007 * EXP(-0.001*AGE)

* Potential growth rate of taproot (kg/ha/d)
      PGTRT = GMASS * PGLTRT
```

Now we have calculated the potential growth rate of the taproot (PGTRT) (kg ha-1 d-1) we can compare it with the growth rate of the taproot (GTRT) (kg ha-1 d-1), which was dependent on the level of reserves. This comparison is needed because of the negative exponential behaviour of PGTRT in time. When age increases, the taproot growth decreases, and less reserves will be allocated to the taproot. The minimum is taken from the source (GTRT) and sink (PGTRT) limited taproot growth.

```
* Comparison between GTRT and PGTRT
      IF (GTRT.GT.PGTRT) THEN
            GTRT = PGTRT
      ELSE
            GTRT = GTRT
      END IF
```

Growth of fine roots

The fine root growth (TGFRT) is calculated as the difference of the root growth and taproot growth.

Afterwards the root growth will be partitioned between the different layers. The growth rate will be higher in layers with many roots than in layers with few roots. The factor (WSERT) prevents root growth in case of drought.

```
* Growth of fine roots
      TGFRT = MAX (0, GRT-GTRT)
      DO I1=1, NLA
            GFRT(I1) = TGFRT * WFRT(I1)/WTFRT * WSERT(I1)
      END DO
```

The death rate of the fine roots depends on the actual root shoot ratio. If the actual root shoot ratio (RSACT) exceeds a setpoint (RSSET), fine roots will die. The death rate is proportional to the relative surplus, divided by a time constant. If the actual root shoot ratio (RSACT) does not exceed setpoint (RSSET), the death rate is zero.

```
* Death rate of fine roots
      RSACT = WTFRT/TADRW
      IF (RSACT.GT.RSSET) THEN
            TDFRT = (WTFRT- RSSET*TADRW)/TAU2
```

```
ELSE
      TDFRT = 0.
END IF

DO I1=1, NLA
DFRT(I1)= TDFRT*WFRT(I1)/WTFRT
END DO
```

At the end of section ITASK=2 the subroutines LEAF and POD will be called, the finish conditions will be defined and the output statements will be given. In the ITASK=3 section no new integral statements are defined, no changes in this section.

4.3.3 subroutine intercept

This subroutine calculates the rain intercepted by the canopy and the rain that reaches the soil. In the former version of the model (Gerritsma, 1995, chapter 6) these calculations were part of subroutine WUPT. This subroutine now will be called in subroutine MODELS.

Rainfall (RAIN) is intercepted by the canopy and reaches the soil as through fall or stem flow. Both, through fall (TFALL) and stem flow (STEMFL) are modelled as a linear function of actual rainfall with a minimum of zero and a maximum of the actual rainfall (Gerritsma, 1995). Intercepted rainfall (PINT) is calculated as the difference between actual rainfall and through fall plus stem flow. The amount of rainfall reaching the soil (RAINS) is the difference between rainfall and interception. There is no correction for the LAI taken into account.

```
* Through fall (TFALL), stem flow (STEMFL) and rainfall interception
(PINT)
      TFALL    = LIMIT (0., RAIN, TFALA*RAIN +TFALB)
      STEMFL   = LIMIT (0., RAIN, STFLA*RAIN +STFLB)
      PINT     = MAX (0., RAIN - TFALL - STEMFL)

* Rainfall reaching the soil (RAINS)
      RAINS    = RAIN - PINT
```

4.3.4 subroutine wupt

This subroutine calculates potential and actual transpiration, the potential water uptake rate, and growth reduction due to water stress.

Initialisation

In the section two variables will be read and the transpiration rate per layer is set to zero.

```
      CALL RDSREA ('TRANSC', TRANSC)
      CALL RDSREA ('WCWET' , WCWET )

*       Transpiration rate per layer is 'zeroed'
      DO I1=1,NL
          TRWL(I1) = 0.
      END DO
```

Potential transpiration

In the evapotranspiration modules (SETPMD, SETMKD, SETPTD) the radiation term and the aerodynamic term of the potential evapotranspiration are calculated. These two variables are provided to the subroutine WUPT and there they are used to calculate the potential canopy transpiration.

```
*       Transpiration and water uptake
*       Potential transpiration
        PTRANS = MAX(0.,(ETRD*(1.-EXP(-0.5*TAI)) + ETAE*MIN(2.0, TAI)
     &                  - 0.5*PINT))
```

Potential water uptake
The potential water uptake rate per unit fine root area (PRWU) is calculated by dividing the potential transpiration (PTRANS) by the total fine root area (AWURTT). The available water level in the soil at which the plant can attain potential transpiration (P), depends on the potential transpiration (PTRANS) and the crop characteristic transpiration rate (TRANSC). For cocoa cultivated under shade this rate is rather low.

```
*       Potential water uptake rate and soil water depletion factor.
        PRWU = MAX (0., PTRANS / AWURTT)
        P    = TRANSC / (TRANSC + PTRANS)
```

Actual transpiration
The actual transpiration rate (ATRANS) depends on the water availability in the soil and the rate at which it can be taken up (PRWU). For each soil layer the contribution to the transpiration rate (TRWL(I1)) is calculated, depending on the the potential transpiration (PTRANS), the area of roots able to take up water in that layer (AWURT(I1)) and a water uptake reduction factor (WSEL(I1)). This reduction factor is calculated separately for each soil layer in the subroutine SWSE (Soil Water Extraction Subroutine)(Gerritsma, 1995). The water uptake reduction factor (WSEL(I1)) is based on the water content of the soil layer and the water depletion factor (P). The transpiration rate per layer (TRWL(I1)) is checked against the water availability (AVAIL). The lowest one is the determining factor. The actual transpiration rate (ATRANS) is the sum of all individual layers.

```
*       Calculate actual transpiration (ATRANS) from
        ATRANS = 0.
        DO 50 I1 = 1, NLA
          CALL SWSE (WCLQT(I1), P, WCWET, WCWPX(I1), WCFCX(I1),
     &               WCSTX(I1), WSEL(I1))
          TRWL(I1) = PRWU * WSEL(I1) * AWURT(I1)
          AVAIL = MAX(0., (WCLQT(I1) - WCWPX(I1)) * TKL(I1) * 1000.)
          IF (TRWL(I1) .GT. AVAIL) TRWL(I1) = AVAIL
          ATRANS = ATRANS + ABS(TRWL(I1))
50      CONTINUE
```

Growth reduction due to water stress
When cocoa grows in a situation where water is limiting, CO_2 assimilation is decreased. A growth reduction due to water stress takes place. The water stress factor (PCEW) is the ratio between actual and potential evpotranspiration.

```
*       Calculate growth reduction due to waterstress
        IF (PTRANS.GT.0.) THEN
          PCEW = ATRANS/PTRANS
        ELSE
          ATRANS = 0.
          PCEW   = 1.
        END IF
```

Crop water requirements are often expressed in terms of the Penman reference evapotranspiration through the use of 'crop factors'. A crop factor for cocoa is calculated (Gerritsma 1995), using a reference evapotranspiration (ETRDG+ETAEG). Short grass is used as reference crop.

```
*       Miscellaneous water related variables
        CROPF  = (PTRANS+EVSC)/(ETRDG+ETAEG)
        PENMAN = ETRD+ETAE
```

4.3.4 subroutine setpmd2

This subroutine calculates the evapotranspiration of cacao and the reference evapotranspiration. The reference crop is always grass. For the calculation of the reference evapotranspiration the model formulations of the subroutine SETPMD of van Kraalingen & Stol (1997) are used.
In case of cacao any crop can be taken. This subroutine is not limited to crops smaller than 2 metres. As mentioned before, now the evapotranspiration equation of Allen *et al.* (1990) will be used. The wind speed is only important to estimate the aerodynamic resistance (RAE); the windfunction itself is not used. In comparison, the reference evapotranspiration calculation uses the windfunction as defined for short grass.

This subroutine is called when the rates are calculated, ITASK = 2.
After the declaration of variables and parameters some checks are executed. A decision has to be made whether the Swinbank or Brunt formula will be used for calculating the longwave radiation.

```
*     decide which calculation for longwave radiation must be used
      IF (ANGA.EQ.0..AND.ANGB.EQ.0.) THEN
*        use Swinbank formula
         ILW = 1
      ELSE IF (ANGA.GT.0..AND.
     &         ANGB.GT.0..AND.
     &        (ANGA+ANGB).GT.0.5.AND.
     &        (ANGA+ANGB).LT.0.9) THEN
*        use Brunt formula
         ILW = 2
      ELSE
         CALL FATALERR ('SETPMD','illegal longwave radiation option')
*         CALL ERROR ('SETPMD','illegal longwave radiation option')
      END IF
```

When SVPS1 is called the humidity variables are calculated. The vapour pressure deficit (VPD) is most important.

```
      CALL SVPS1 (TMDA, VPS, VPSL)
      HUM = VP/VPS

      IF (HUM.GT.1.) THEN
         VPD = 0.
         IF (HUM.GT.1.4) WRITE (*,'(2A)') ' WARNING from SETPMD:',
     &      ' Vapour pressure more than 40% greater than saturated !'
      ELSE
         VPD = VPS-VP
      END IF
```

Subroutine SASTRO provides the variables for the calculation of the long wave and net radiation, using the Ångström formula.

```
*     Long wave radiation (J/m2/s and J/m2/d) and net radiation

      CALL SASTRO (IDOY,LAT,
     &             DUMR1,ANGOT,DAYL,DUMR3,DUMR4,DUMR5,DUMR6,DUMR7)
      DATMTR = LIMIT (0.,1.,RDD/ANGOT)

      RDLOI = SIGMA*(TMDA+273.16)**4
      RDLO  = 86400.*RDLOI
      IF (ILW.EQ.1) THEN
*        Swinbank formula for net long wave radiation
         RDLII = DATMTR*(5.31E-13*(TMDA+273.16)**6-RDLOI)/0.7+RDLOI
         RDLI  = 86400.*RDLII
      ELSE IF (ILW.EQ.2) THEN
*        Brunt formula for net long wave radiation
          CLEAR = LIMIT (0., 1., (DATMTR-ANGA)/ANGB)
         RDLII = SIGMA*(TMDA+273.16)**4*(1.-(0.53-0.212*SQRT(VP))*
     &          (0.2+0.8*CLEAR))
         RDLI  = 86400.*RDLII
      END IF

     RDN = (1.-RF)*RDD+RDLI-RDLO
```

The radiation and aerodynamic terms `ETRD` and `ETAE` will be calculated, using the formula of Allen *et al.* (1990)(see section 3.2.1). The canopy resistance `RCAN` is equal to the leaf resistance `RLEAF` divided by three, an empirical rule observed by Kelliher *et al.* (1995). `RLEAF` is a constant, based on the values used by Radersma & De Ridder (1996).

The aerodynamic term `ETAE` as referred to by Allen *et al.* (1990) is expressed per second. To get daily evapotranspiration the aerodynamic term has to be multiplied by 86400. The aerodynamic term `ETAE` too is only valid during the daytime. That explains the factor `DAYL/24`. In the night the aerodynamic part is zero.

```
*     Actual water loss (separated in radiation term and
*     aerodynamic term) and resistance to transfer of vapour (s/m)
*     and estimated temperature difference

      RCAN = RLEAF/3

      ETRD = (VPSL*RDN)/(LHVAP*(VPSL + PSCH*(1+RCAN/RAE)))
      ETAE = (DAYL/24) *((RHOCP*VPD)/(RAE/86400))/
     &                          (LHVAP*(VPSL + PSCH*(1+RCAN/RAE)))
```

The reference evapotranspiration is calculated as defined by van Kraalingen & Stol (1997). `ISURF` is 3, a short grass surface. See for more information van Kraalingen & Stol (1997).

4.4 Model parameterisation

Before the model can be run the values for the parameters and variables need to be selected. The following data are required: data about the cocoa crop, but also data representing the environment: physical soil and weather data.

In this chapter the data used for a simulation run representative for Ghana are described. The complete parameter set is listed in the plant data file CASE2.dat. This list can be found in Appendix 2. For further information, see Gerritsma (1995).

Data used in CASE2
The Ångström formula, the regression formula between sunshine duration and radiation needs two parameters (ANGA and ANGB). Various values have been found for these parameters for different locations and different times of year. Frere & Popov (1979) gave general estimates for the wet tropics (0.29 and 0.41). For Ghana, Tafo the regression parameters are calculated too (Gerritsma, 1999, pers. com):

```
ANGA = 0.22 ; ANGB = 0.37
```

The planting density is given by the parameter NPL. In practice planting densities can range from about 500 to 3000 trees ha^{-1}, depending on the age of the planting and agricultural practice (Gerritsma, 1995). From my own experience in West Africa the planting density ranges between 900 and 1050 trees ha^{-1}.

```
NPL = 920.
```

For the initialisation trees of 51 months old are used, because then the data of Thong & Ng (1978) can be used. The weight of wood, leaves and pods are specified by WWDI, WLVI and WPDI respectively. The initialisation of the roots take is done differently. The length of the taproot LTRT determines the diameter (DTRT) and the weight (WTRT) of the taproot. The initial length LTRTI is read from the table LTRTB. The weight of the fine roots can be approximated with a negative exponential function (see section 4.3.1). Parameter WMAX (kg DM ha-1 m-1), the maximum fine root biomass at depth zero is read from table WMAXTB. Parameter KA determines the rate of exponential decrease (m-1).

```
AGEI   = 1525.     ! [days after field planting] (51 months)
WWDI   = 15.06     ! [kg DM tree-1] (Thong & Ng, 1978; 51 months)
WLVI   =  7.64     ! [kg DM tree-1] (Thong & Ng, 1978; 51 months)
WPDI   =  3.09     ! [kg DM tree-1] (Thong & Ng, 1978; 51 months)

* Length tap root (x,y = age(d),length(m))(Himme, 1959)
LTRTB = 0.,0., 100.,0.37,  5110.,1.3,  9125.,1.5,  20000.,1.5

*Maximum fine roots in the soil depends on age (x,y = age (d),
* maximum fine root density (kg ha-1 m-1))
*(After Kummerow, 1981)
WMAXTB = 0.,0., 2190.,2830., 5470.,13910., 20000.,13910.

KA = 9.
```

Two estimates for leaf age are required, maximum and minimum leaf age MAXLAG and MINLAG. In shaded cocoa the maximum leaf age is estimated to be a year (Alvim, 1967; Boyer, 1973). Murray (1953) found that the maximum leaf age is strongly reduced in unshaded cocoa. Sale (1968) reported the lowest minimum leaf age: around 90 days for cocoa grown in Trinidad at the highest temperature treatment.
A maximum leaf age of 365 days provides realistic results for Ghana. For the minimum leaf age a life span of 60 days is chosen for Ghanaian conditions. In the dry period from November till March severe water stress is simulated. The trees in the model do not survive the dry period if the minimum leaf age is more than 60. The maintenance costs are too high. If the minimum leaf age is too low, many leaves will fall in the dry period. Then the photosynthesis rate and the growth are low too. The trees will recover very slowly from the dry period.

```
MAXLAG = 365. ; MINLAG = 60.
```

The potential growth rate of the length of the taproot per time is calculated from the experimental data of Himme (1959) (see figure 3.3.1). When running the model it became clear that the taproot was growing too slow, when using the values of the visually fitted trend line (`PGLA = 0.0007` and `PGLB = 0.001`). The ratio between taproot and fine roots became 1:1.
The assumption can be made that the trees in the experiments did not grow under non-limited conditions, the regression parameters have been changed by trial and error. The growth in the beginning is faster (`PGLA` is higher), but the decrease of the growth rate is not slower (`PGLB` is equal) (see figure 4.4.1). The experiments were done in Belgian Congo, and Himme (1959) described some physiologically shallow soils. He mentions too that the cocoa trees are very sensitive to drought. To do such an observation the growth conditions can not always have been potential. The ratio between taproot and fine roots now more or less remains 1:4. Apparently the sensitivity of these paramaters is high.

```
PGLA = 0.0008 ; PGLB = 0.001
```

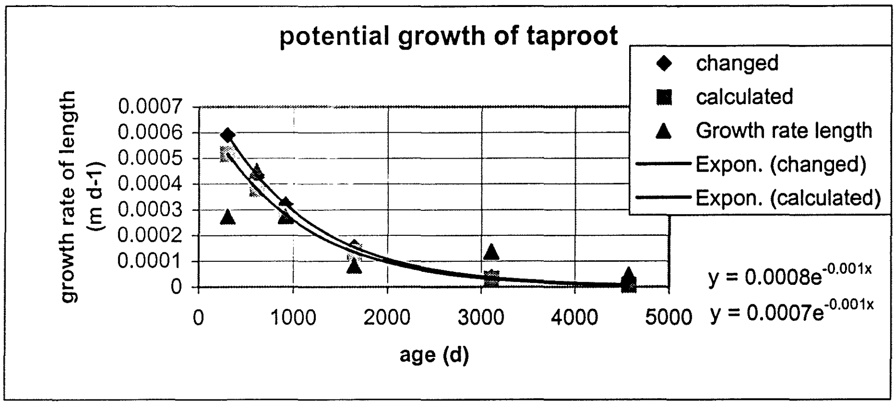


Figure 4.4.1: Changed graph of potential taproot length growth (see figure 3.3.1) (after Himme, 1959).

For the volumetric mass of cocoa wood Boyer (1973) found a value of 340 kg m^{-3}, by averaging the results of 18 cocoa trees. Daymond found a value of 500 (Gerritsma, 1999, pers. com.). For specific mass of wood used in the model is based on Boyers value. According to Ray Gurries, researcher at the department of Forest Ecology and Management in Madison, USA it is reasonable to state that the root wood specific gravity is about 10-15% heavier than stems, due to a greater percentage of compressed wood. Therefore in the model the volumetric gravity is set to 390 (340 + 0.15 * 340).

```
SW = 390.
```

The root-shoot ratio in cocoa is considered to be 1:4. The partitioning of reserves to shoot and root is based on this ratio. The setpoint for the death rate of fine roots (`RSSET`) is defined slightly differently. It is the ratio between the fine roots and the shoot. The ratio between taproot and fine roots is 1:4 (`PTRT` and `PFRT`), too. The fine root-shoot ratio (`RSSET`) can be calculated: 0.25 x `PFRT`.

```
PTRT = 0.2
PFRT = 0.8
RSSET = 0.2
```

The reserve factor determines the quantity of reserves that must be 'stored' before growth can occur. The name of this storage bulk is `WRES`. When this bulk is larger, the trees can survive more severe dry periods, because it takes longer for the reserves are depleted. When this bulk has to be very large before growth can occur, it takes a long time after the dry period before new leaves appear.

```
RESF = 1.25
```

A time coefficient appears equal to the time that would be needed for the model to reach its equilibrium. The time coefficient (TAU) (d) represents the reaction rate of the model (Leffelaar, 1993). For the depletion rate of the reserves (TAU) and the death rate of the fine roots (TAU2) a time coefficient is implemented. In case of the death rate of the reserves it means that the reserves are not used all within one day. The values of TAU and TAU2 are not correct strictly speaking, because in general TAU has to be one tenth of the time step. These values however were found by experimenting with the model.

```
TAU = 10. ; TAU2 = 1.
```

Data used in subroutine SETPMD2

The resistance parameters RAE and RLEAF for cocoa under West African conditions are estimated by Radersma & De Ridder (1996). To find the value of the aerodynamic resistance (RAE), they assumed a wind speed at canopy height of 1.5 m/s. The value of the leaf resistance parameter (RLEAF) is estimated for a situation where no water stress occurs. When there is water shortage, the leaf resistance will increase. To calculate the potential evapotranspiration potential environmental circumstances are assumed.

```
RLEAF = 150. ; RAE = 38.
```

5 Results and discussion

In this chapter the results of the simulation runs are described. There is no complete dataset available for West African conditions, but for Malaysian conditions weather data as well as yield data are available. Therefore the model is tested using a scenario for cocoa grown in Malaysia, Sabah, at BAL estate (paragraph 5.1). The two versions of CASE2, 1.1 and 1.2 are compared with observed yields. In paragraph 5.2 the simulation results for the two versions of CASE2 for West African conditions are compared. There are no yield data from observations available for West Africa for a period where weather data are available. The simulation outputs can not be verified. In paragraph 5.3 the model is discussed, particularly the way to model the partitioning of the reserves within the cocoa tree. In paragraph 5.4 concluding remarks are stated.

5.1 Simulation results for Malaysia

To test the model observations of cocoa growth and yield are needed. The management practices, plant characteristics and environmental conditions should be known to make useful comparisons possible. Comprehensive data sets such as these are scarce. Gerritsma (1995) found an appropriate set only for BAL estate in Malaysia. See Gerritsma (1995, chapter 6.10) for the model parameterisation for Malaysian conditions.

Both the models were tested.The start of the simulation run was in 1983 at day 120. The trees were of `AGE = 0.`, that means zero days after field planting. The age of the plants is 12 months.

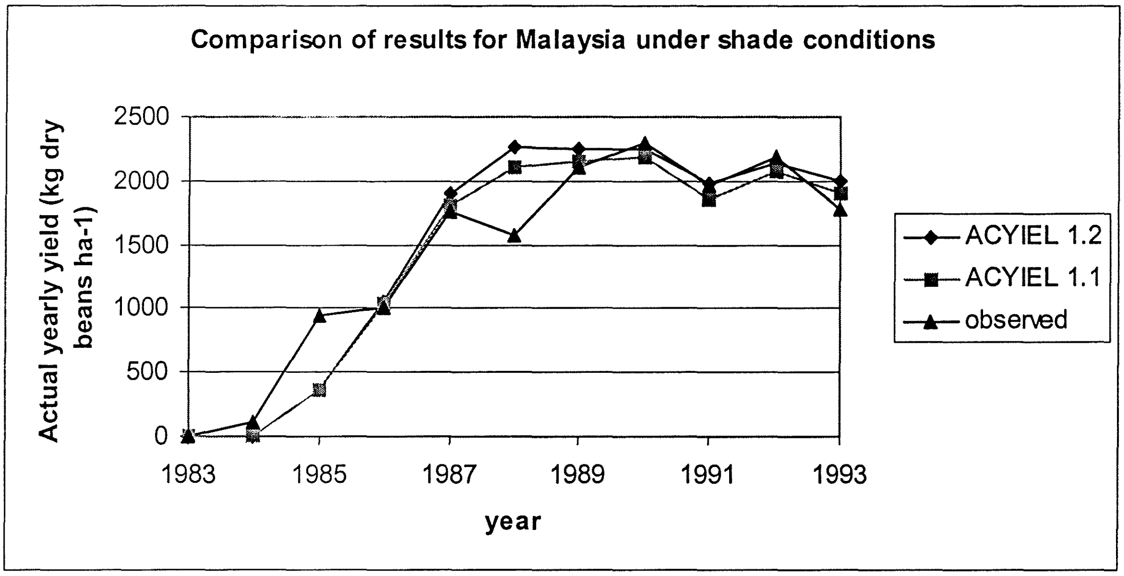


Figure 5.1.1: Simulated and observed cocoa yields at BAL, Malaysia.

As can be seen in figure 5.1.1 the actual yields calculated by both models are very close to the observed yields. The models both realistically follow the 11 year trend. From 1987 on, the trend can be explained by the rainfall pattern (Appendix 3a). Until 1987 the cocoa plantation was not yet fully developped.
Only observed data about the actual yield were available to compare with the simulation results. There were no observed data about LAI, root shoot ratio, root weight, growth periodicity.
There seems to be no difference between the results of the two versions of CASE2. The actual annual yield, as well as the LAI, weight of roots, total dry weight (Appendix 3 b-d) do not differ much.
In version 1.1 and 1.2 the water relations are modelled differently. The changes in version 1.2 do not affect the yield. Water stress still plays a role because there is a difference in actual annual yield between simulated potential and waterlimited situations Apparently, the yield

reducing effects of water stress are described sufficiently in version 1.1. The rainfall in Malaysia is evenly distributed during the year. Water stress is less severe than in West Africa.

5.2 Simulation results for Ghana

The data needed as input for the model for West African conditions are described in paragraph 4.4. The minimum and maximum leaf age, the Ångström parameters, the planting density and weather data changed. As mentioned earlier observed yield or other crop growth data were not available. It was not possible to make a comparison between simulated and observed results.

The start of the simulation run was in 1983 at day 120. The trees were of `AGE = 1525.`, that means 1525 days after field planting. The age of the plants is 5 years. The trees are still in full crop. In the simulation runs for Ghana the shade trees are eliminated; `LAI` of the shade trees is set to zero.

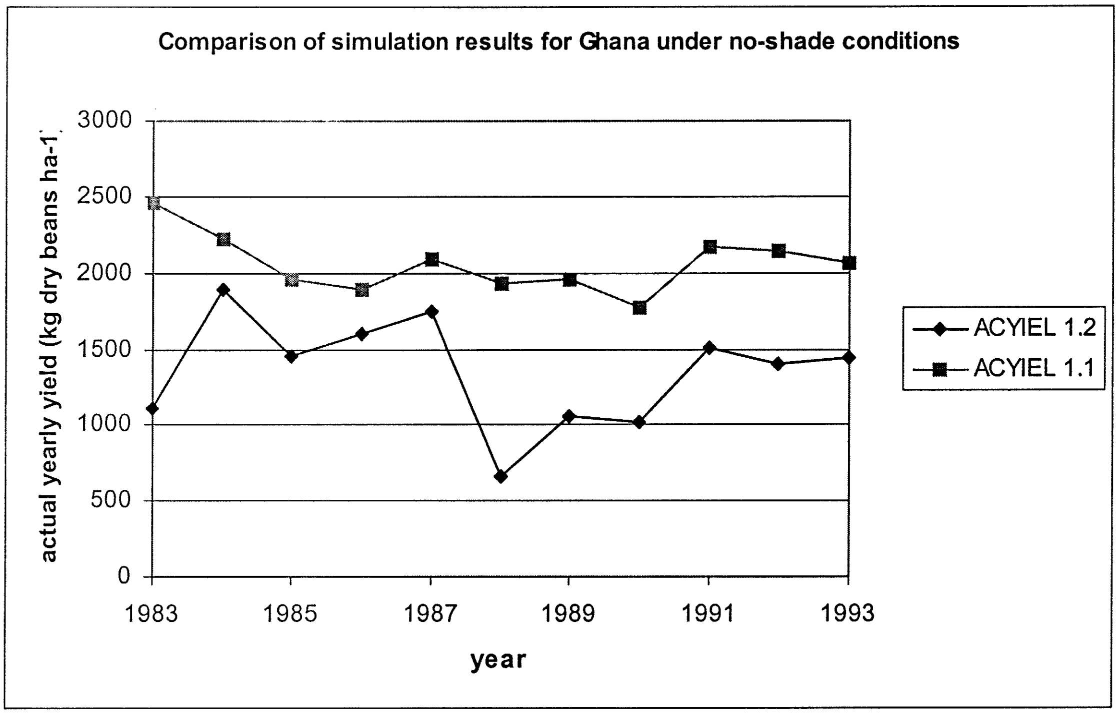


Figure 5.2.1: Simulated cocoa yields in Ghana, Tafo.

Big differences can be observed between the actual annual yields simulated by the two versions of CASE2. These differences can be explained by differences in the leaf area index (LAI) (Figure 5.2.2). The LAI in the plot is calculated by using the average of simulation outputs every 10 days. If the photosynthetic rate decreases, the yield will be lower. The LAI is the yield determining factor.

As can be seen in figure 5.2.2 in the version 1.2 run the mean LAI decreases enourmously in the year 1988. This can not be explained by the low amount of rain during the year. Table 5.2.1 compares the yearly rainfall and yield of 1986 with those of 1988.

Year	Yearly rainfall (mm)	Yearly yield (kg dry beans ha-1)
1986	858	1600
1988	989	650

Table 5.2.1: Comparison of yearly rainfall and yield in 1986 and 1988.

The yield in 1988 is lower, while the yearly rainfall is higher. The amount of rainfall in the main dry period, from November till March seems to be more important (see table 5.2.2).

Year	Rainfall from January till March (mm)	Yearly yield (kg dry beans ha-1)
1986	284	1600
1988	190	650

Table 5.2.2: Comparison of rainfall in main dry period and yearly yield in 1986 and 1988.

The LAI in 1988 becomes low in the dry period, below 0.5. In version 1.2 the cocoa trees do not 'recover'. The partitioning of reserves to the leaves is not enough to attain a LAI of about 4. The cocoa trees in version 1.1 (figure 5.2.1;1.1) do not suffer as much from water stress. The actual annual yield fluctuates around 2000 kg ha-1 and the mean LAI is about 7.

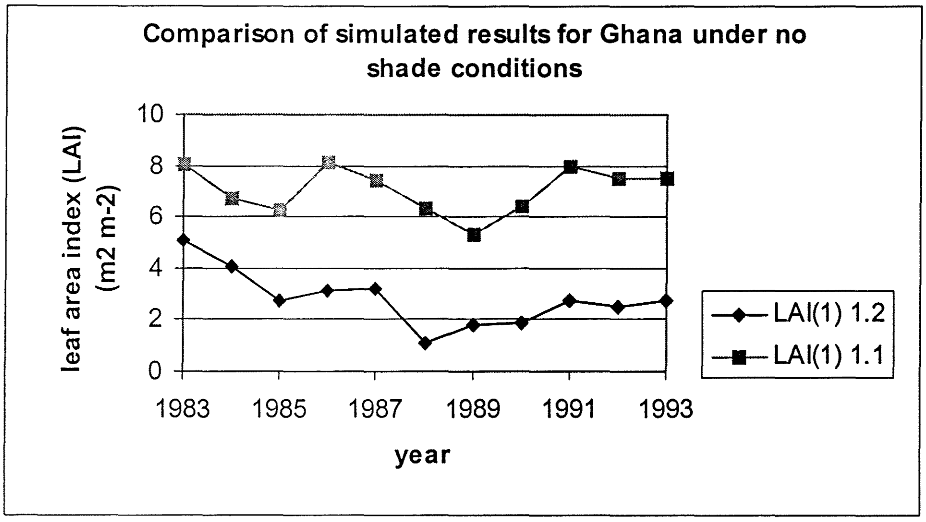


Figure 5.2.2: Simulated LAI in Ghana, Tafo.

5.3 Discussion

Partitioning

The partitioning of the reserves is fixed by a table in both the models (see figure 4.3.2). When the trees are mature, a fixed percentage of the assimilates is always partitioned to the leaves, pods, wood and roots. No shift can take place during a year. Even when the LAI is below 0.5, still 32% , 20% and 18% of the reserves are allocated to the wood, roots and pods respectively. As can be seen from figure 5.2.2 that is not realistic: in version 1.2 the cocoa trees can not recover from the low LAI.

The mechanisms of partitioning in cocoa are not exactly known (Gerritsma, pers. com.). The processes of leaf growth and fall in cocoa are not similar to these processes for temperate trees. A dry period in West Africa is not like a winter in Europe. The processes of leaf growth and fall in temperate trees are temperature related. For cocoa it is not so easy. The trigger for flushing does not depend on one factor, as for example water. There are cases in which the flushes started before the rain, (Alvim, 1972) whereas in other cases flushing is triggered by rain.

Many hypotheses about the periodicity of flushing and cropping within a year have been proposed. Flushing, for example has been correlated to soil moisture, soil temperature, rainfall, maximum air temperature and shade (Gerritsma, 1995). Hutcheon (1977) states that rainfall pattern and solar radiation have important effects on leaf and flower production, and determine the size and timing of the crop. Although it seems that the periodicity of cropping is initiated by the seasonal pattern of photosynthesis. Owusu *et al.* (1978) showed that in Ghana peaks of flushing and flowering coincided with the major peaks of sunshine hours, but also with the period of maximum levels of free sugars in cocoa trees. They put forward the more integrated theory that flushing and flowering are controlled by the carbohydrate status of the tree, which is dependent on the amount of sunlight.

The version 1.3 of the model takes into account that the partitioning of the reserves changes if the LAI falls below a certain value. It is assumed that if the LAI falls below 3 in a mature tree, the reserves within the shoot are completely partitioned to the leaves (`FLV = 1.`). The partitioning between root and shoot remains the same. If the LAI is below 3, only the leaves and the roots will grow.

```
IF ((LAI(1).LT.3.).AND.(AGE.GE.600.)) THEN
          FSH = 0.8
          FLV = 1.
          FWD = 0.
          FPD = 0.
        ELSE
*         Dry matter partitioning
          FSH    = LINT (FSHTB, IFSHN, AGE)
          FLV    = LINT (FLVTB, IFLVN, AGE)
          FWD    = LINT (FWDTB, IFWDN, AGE)
          FPD    = LINT (FPDTB, IFPDN, AGE)
        END IF

        FRT    = 1. - FSH
        FRTF   = PFRT * FRT
        TRTF   = PTRT * FRT
```

In figure 5.3.1 and 5.3.2 the yield respectively LAI are plotted for the simulation results of the three different versions.

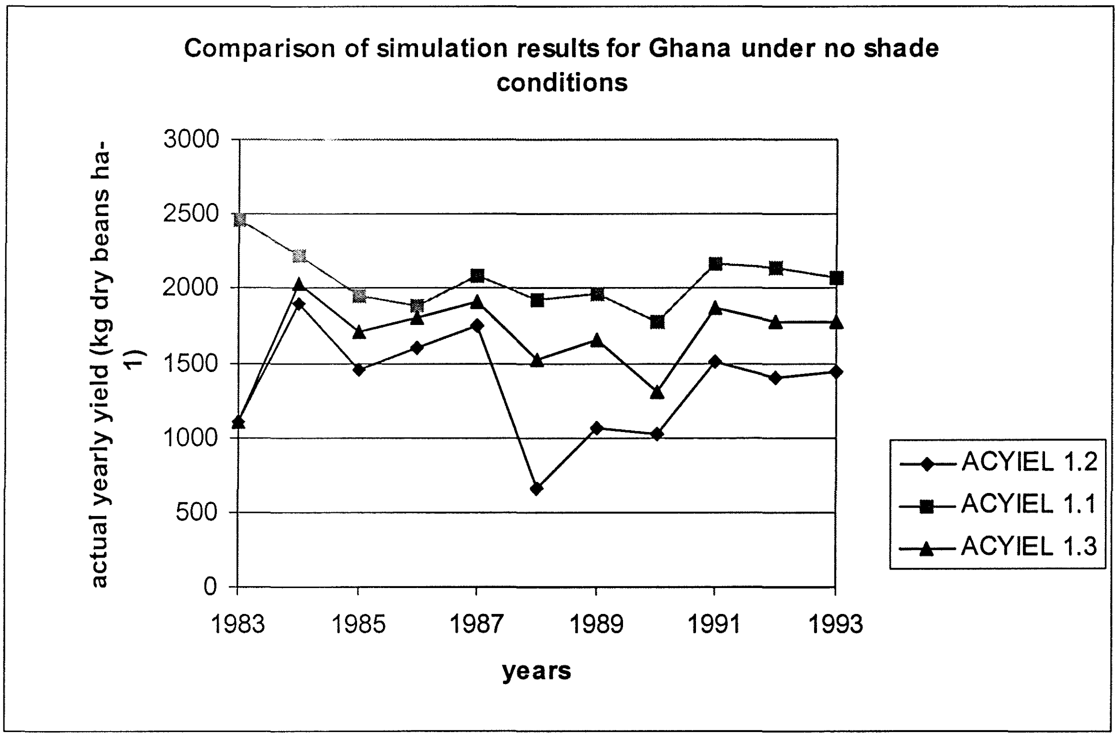


Figure 5.3.1: Simulated yields for Ghana, Tafo.

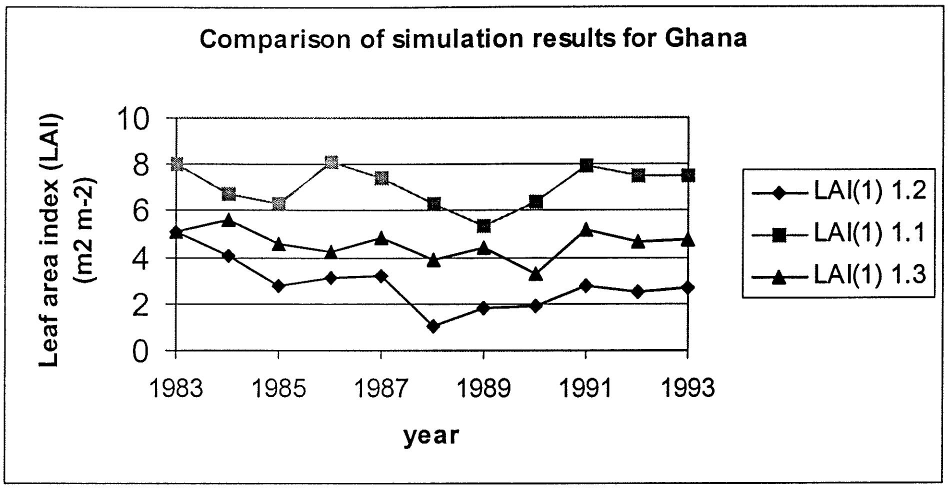


Figure 5.3.2: Simulated LAI for Ghana, Tafo.

As illustrated in figure 5.3.2, version 1.3 run, cocoa trees recover better from the dry period. Low LAI's (less than 1) still can occur. High values for the LAI are found too, up to 12. Extreme high values are not realistic. May be a same kind of partitioning statement must be made at LAI's higher than 10.

The consequences of this changed partitioning are tested for the Malaysian results. Figure 5.3.4 shows that there are only minor changes.

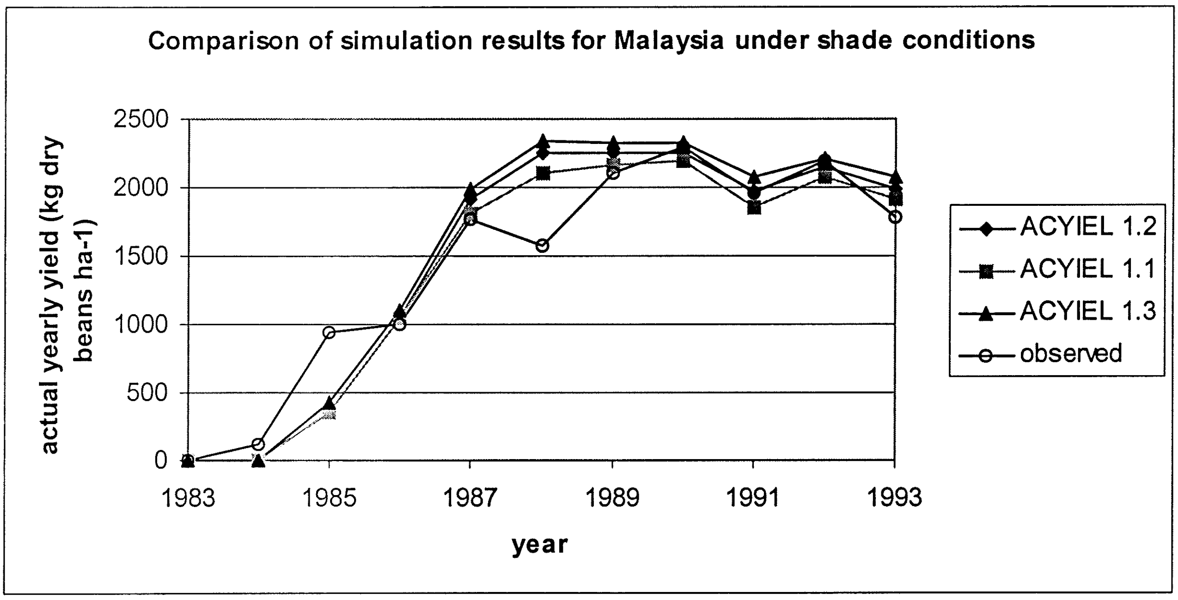


Figure 5.3.4: Simulated and observed actual yearly yields in Malaysia at BAL estate.

Evapotranspiration

The potential evapotranspiration data presented in figure 5.4.4 belong to the same simulation run as the annual yield data for Ghana as presented in figure 5.3.1. The plotted potential evapotranspiration is the sum of the radiation and aerodynamic part of the Penman Monteith equation (ETRD+ETAE). It is not PTRANS as calculated in subroutine WUPT.

The difference between the version 1.1 and 1.2 run are not so big. The difference is less than ten percent. As expected, the simulation run with the new evapotranspiration module (1.2)(see section 4.3.4) has higher evapotranspiration values than the run with the old module (1.1)(see van Kraalingen, 1995). The evapotranspiration as calculated in subroutine SETPMD2 is more

realistic for tree crops. As explained in section 3.2.2 tree crops generally have a larger transpiration than annuals.
That run 1.2 has a higher evapotranspiration as the run 1.3 needs to be explained. Run 1.3 has a larger LAI than run 1.2 (see figure 5.3.2). Intuitively it is expected that the run 1.3 with more leaves will have a higher level of transpiration. That is the opposite of what is seen in figure 5.3.4. The explanation for this is that a lower LAI causes a lower reflection coefficient (RF) and therefore a higher net radiation. The radiation term ETRD and therefore the evapotranspiration will be both higher.

Box 5.3.1: Modelling the reflection coefficient.

The reflection coefficient (RF) is calculated in subroutine MODELS. RFS is the reflection coefficient of the soil.

```
      * Total reflection
        RF  = RFS*EXP(-0.5*TAI)+0.25*(1.-EXP(-0.5*TAI))
```

The net radiation (RDN) is calculated in subroutine SETPMD . The net radiation (RDN) is determined by the reflection coefficient, the daily short wave radiation (RDD) and long wave radiation (RDLI, RDLO).

```
      * Net radiation
        RDN = (1.-RF)*RDD+RDLI-RDLO
```

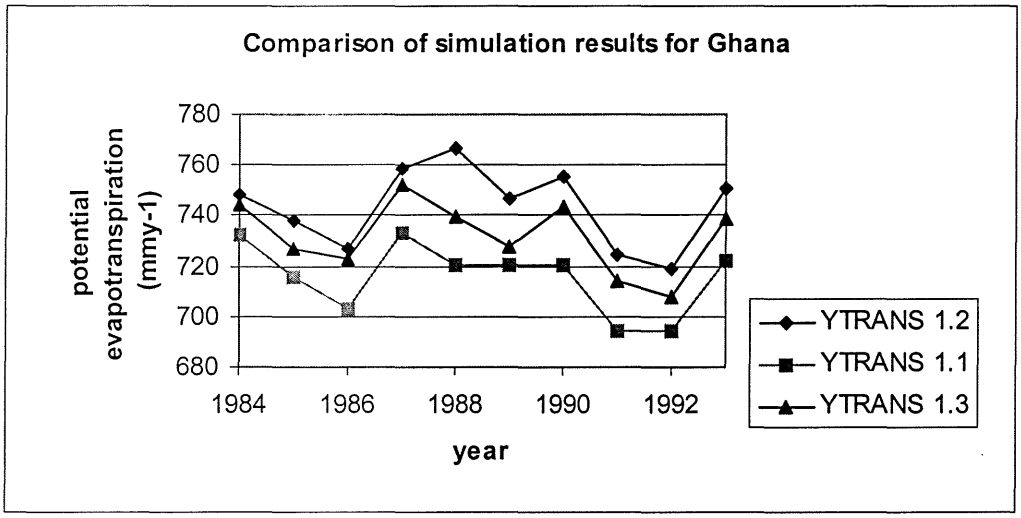


Figure 5.3.4: Potential evapotranspiration for Ghana.

It is not useful to plot PTRANS and ATRANS for the several runs as calculated in the model. The LAI's are used to calculate this variables. Because of the big differences between the LAI's in the different runs, the results are not comparable.

Taproot growth
The growth of the taproot is still described as a first order process in the model. That is not ideal, but there is not enough knowledge about the growth rate available to develop a more mechanistic description.

Sensitivity analysis
No explicit sensitivity analysis was done on the parameters. However, while running the model it became clear which parameters are important to get realistic results.
If the growth of the taproot is too fast, the ratio between taproot and fine roots diverges too strongly. If the growth of the taproot is too slow, the depth from where water can be taken up is too shallow. The trees in the model suffer from waterstress.
The minimum and maximum leaf age are important parameters. In the dry period the amount of leaves that fallis determined by the defined minimum and maximum leaf age. Too many leaves in the dry period cause a depletion of the reserves; this means the minimum leaf age is

too high. If there are too few leaves (the minimum leaf age is too low), the photosynthetic rate is slow and recovering after the dry season takes a long time.
The level of reserves that must be available before growth can occur is also a critical parameter. This level must be high enough for the tree to survive the dry season. When this level is defined too high, the amount of growth decreases.
In version 1.3 the partitioning of assimilates is defined by the state of the `LAI`. In version 1.3 the leaves receive 100% of the within-shoot reserves when the LAI is below three. Yield does not differ much when the partitioning changes if `LAI = 4.` or `LAI = 5.`. When `LAI = 4.` the yield increases with regard to `LAI = 3.`. When `LAI = 5.` the yield decreases with regard to `LAI = 3.`. When `LAI = 5.` the yield is reduced because of the relatively great priority given to leaf growth. Until the `LAI = 5.` pods do not grow.

5.4 Concluding remarks

In this thesis a theoretical framework for simulating cocoa under West African conditions has been developed. Under Malaysian conditions the three versions of the model fit well with the observed values. For the West African situation each of three versions of the model give different simulation results. Because there is no data set available for both observed yield and weather data, it is not possible to compare the results with the observed data. Therefore the theoretical framework can not be validated for West African conditions.

In my opinion there are two aspects which require further research.

1. Data about yield, LAI, root growth, root:shoot ratio need to be collected to test the theoretical framework for West African conditions. It is also important that a complete weather data set is collected .

2. From a scientific point of view it would be interesting to investigate the mechanisms of the partitioning of assimilates in cocoa. If the mechanisms of partitioning are more clear, the periodicity of flushing and yielding can be understood.

On a more practical level there are a few comments I would like to add.
If the plantations in Togo were be managed well, the yields would be higher than they are now. Management practices to increase yield are: weeding, pruning, control of pests and diseases. Almost 80% of the plantations is older than 40 years. A cocoa plantation gives a profitable yield until it is 25-30 years. Regeneration of plantations is needed.
When these yield increasing measures are common practice for farmers, application of phosphate rock will be more useful.

Acknowledgement

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Subroutine case2

```
*----------------------------------------------------------*
*  SUBROUTINE CASE2, version 1.2                            *
*                                                           *
*  Authors: Wouter Gerritsma & Liesje Mommer                *
*                                                           *
*  Date   : March 1999                                      *
*                                                           *
* Purpose: This subroutine is the cacao version of SUCROS,  *
* to calculate growth in situations of water limited        *
production.                                                 *
*
*  FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
*
*  name   type meaning                                    units
class *
*  ----   ---- -------                                    -----  ----
- *
* ITASK   I4  Task that subroutine should perform          -       I
*
* IUNITD  I4  Unit that can be used for input files        -       I
*
* IUNITL  I4  Unit used for log  file                      -       I
*
* FILEP   C*  Name of file with plant data                 -       I
*
* OUTPUT  L4  Flag to indicate if output should be done    -       I
*
* TERMNL  L4  Flag to indicate if simulation is to stop    -
I/O *
* IDOY    I4  Day number within year of simulation (INTEGER) d     I
*
* DELT    R4  Time step of integration                     d       I
*
* TIME    R4  Time of simulation                           d       I
*
* STTIME  R4  Start time of the simulation                 d       I
*
* LAT     R4  Latitude of site                         dec.degr.   I
*
* RDD     R4  Daily shortwave radiation                 J/m2/d     I
*
* FRPAR   R4  Fraction PAR in shortwave radiation          -       I
*
* TMMN    R4  Daily minimum temperature               degrees C    I
*
* TMMX    R4  Daily maximum temperature               degrees C    I
*
* NLXM    I4  no. of layers as declared in calling program -       I
*
* NL      I4  number of layers specified in input file          -      I
*
* TRWL[]  R4  actual transpiration rate per layer            mm/d      I
*
* TKL[]   R4  thickness of soil compartments                    m      I
*
* ZRTMS   R4  maximuming depth as soil characteristic           -      I
*
* WCLQT[] R4  volumetric soil water content per layer     m3 m-3      I
*
* WCWPX[] R4  volumetric water content at wilting point   m3 m-3      I
*
* WCFCX[] R4  volumetric water content at field capacity m3 m-3       I
*
* WCSTX[] R4  volumetric water content at saturation      m3 m-3      I
*
* EVSC    R4  actual (realized) evaporation rate             mm/d      O
*
* ETRD    R4  Radiation driven part of ETPMD                 mm/d      O
*
* ETAE    R4  Dryness driven part of ETPMD                   mm/d      O
*
* RAIN    R4  Daily amount of rainfall                       mm/d      I
*
* RAINS   R4  Daily amount of rainfall reaching the soil     mm/d      O
*
* TAI     R4  Total area index                                  -      O
*
* PRODL   R4  Production level                                  -   IN,O
*
*
*
* FATAL ERROR CHECKS (execution terminated, message)
*
* condition: FSO < -0.001, DELT < 1, LAT < -98, RDD < -98, TMMN < -98
*
*            TMMX < -98, checks internal to other subroutines
*
*
*
* SUBROUTINES and FUNCTIONS called : TOTASC,
*
*              ERROR, OUTCOM, OUTDAT, RDINIT, RDSREA, RDAREA
*
*              OUTARR
*
* FILE usage : IUNITP
*
*----------------------------------------------------------*
      SUBROUTINE CASE2  (PLTMOD, ITASK, IUNITD, IUNITO, IUNITL,
     &                   FILEP, OUTPUT, TERMNL,
     &                   DOY, IDOY, IYEAR, DELT, TIME,
```

```
     &                   STTIME, LAT, FRPAR, RDD, TMMN, TMMX,
     &                   NLXM, NL, TRWL, TKL   , ZRTMS,
     &                   WCLQT , WCWPX , WCFCX , WCSTX ,
     &                   EVSC  , ETRD  , ETAE  , PINT,
     &                   GAI   , TAI   ,RAIN )

      IMPLICIT REAL (A-Z)
*      IMPLICIT NONE

*     Formal parameters
      INTEGER   ITASK     , IUNITO    , IUNITD, IUNITL, IDOY, IYEAR
      REAL      DOY       , DELT      , TIME  , STTIME
      REAL      ZRTMS     , EVSC      , ETRD  , ETAE  , PINT
      REAL      GAI       , TAI       ,RAIN
      LOGICAL   OUTPUT    , TERMNL
      CHARACTER PLTMOD*(*), FILEP*(*)

*     Water balance declarations
      INTEGER NLXM, NL
      REAL TRWL(NLXM) , TKL(NLXM)
      REAL WCLQT(NLXM), WCWPX(NLXM), WCFCX(NLXM), WCSTX(NLXM)

*     Standard local declarations
      INTEGER NLA, I1
      REAL AWURTT, PTRANS, ATRANS, PCEW
      REAL PENMAN, CROPF, WRT,   WRES, AGE, AGEI
      REAL GLV, WLVG, DLV
      REAL TMAV, GPD, YIELD

*     Root declarations
      REAL FRT
      REAL GRT
      REAL SW

*     Taproot growth declarations
      REAL TRTF
      REAL LTRT, WTRT
      REAL GTRT, PGLTRT, GMASS, PGTRT
      REAL PI
      PARAMETER(PI= 3.1415927)

*     Fine root growth declarations
      REAL FRTF
      REAL TGFRT, TDFRT, WTFRT, WTFRTD
      INTEGER NLBM
      PARAMETER (NLBM = 10)
      REAL WSERT(NLBM), GFRT(NLBM), WFRT(NLBM)
      REAL AWURT(NLBM), DFRT(NLBM)

*     Root:shoot ratio
      REAL RSSET, RSACT

*     Reserve factor
      REAL RESF

*     Partitioning parameters
      REAL PTRT, PFRT

*     Species parameter
      INTEGER INS
      PARAMETER (INS = 2)
      REAL  LAI(INS), SAI(INS), HGHT(INS),  HGHL(INS), KDF(INS),
      KS(INS)
      REAL AMAX(INS), EFF(INS), DTGA(INS), FRABS(INS)

*     Miscellaneous
      INTEGER IDOYO

*     Time coefficient tau
      REAL TAU , TAU2

*     Taproot growth parameters
      REAL PGLA, PGLB

*     Function table declarations
      INTEGER ITABLE
      PARAMETER (ITABLE=100)
      REAL      AMTMPT(ITABLE)
      INTEGER   IAMTMN

      REAL     FSHTB(ITABLE),FWDTB(ITABLE),FLVTB(ITABLE),FPDTB(ITABLE)
      INTEGER   IFSHN        ,IFWDN        ,IFLVN        ,IFPDN

      REAL      TSLAIL(ITABLE)
      INTEGER   ISLAIL

      REAL      TSLAIT(ITABLE)
      INTEGER   ISLAIT

      SAVE

      IF (DELT.LT.1.0) CALL FATALERR
     &   ('CASE2','DELT too small for CASE2')

      IF (ITASK.EQ.1) THEN
*        ----------------------
*        Initialization section
*        ----------------------

*        Send title(s) to output file
         CALL OUTCOM (PLTMOD)
         CALL OUTCOM ('CASE2, CAcao Simulation Engine   Version 2.0')
         CALL OUTCOM (' Production level 2, Nov. 1996           ')
```

```
*       Intialize input file
        CALL RDINIT (IUNITD  , IUNITL, FILEP)

*       Read plant parameters from file

*       Planting density and age
        CALL RDSREA ('NPL'    , NPL    )              ! trees ha-1
        CALL RDSREA ('AGEI'   , AGEI   )

*       Initial weight of palm components (per tree basis)
        CALL RDSREA ('WWDI'   , WWDI  )             ! [kg DM tree-1]
        CALL RDSREA ('WLVI'   , WLVI  )
        CALL RDSREA ('WPDI'   , WPDI  )
        CALL RDSREA ('SW', SW)
*       Photosynthesis  parameters
        CALL RDSREA ('AMX'    , AMX    )
! maximum rate of photosynthesis
        CALL RDSREA ('EFF'    , EFF(1))
! intial light use efficiency
        CALL RDAREA ('AMTMPT', AMTMPT,  ITABLE, IAMTMN)
! Temperature effect photosynthesis

        CALL RDSREA ('KDFL'    , KDF(1))
! extinction coefficient for diffuse light
        CALL RDSREA ('KDFT'    , KS(1))
! extinction coefficient for diffuse light

*       Tissue maintenance coefficients
        CALL RDSREA ('MAINFRT', MAINFRT)
        CALL RDSREA ('MAINTRT', MAINTRT)
        CALL RDSREA ('MAINWD', MAINWD)
        CALL RDSREA ('MAINLV', MAINLV)
        CALL RDSREA ('MAINPD', MAINPD)

        CALL RDSREA ('Q10'    , Q10    )
        CALL RDSREA ('TREF'   , TREF   )

*       Tissue asssimilate requirements
        CALL RDSREA ('ASRQFRT', ASRQFRT)
        CALL RDSREA ('ASRQTRT', ASRQTRT)
        CALL RDSREA ('ASRQWD', ASRQWD)
        CALL RDSREA ('ASRQLV', ASRQLV)
        CALL RDSREA ('ASRQPD', ASRQPD)

*       Tissue carbon content
        CALL RDSREA ('CFFRT'  , CFFRT )
        CALL RDSREA ('CFTRT'  , CFTRT )
        CALL RDSREA ('CFWD'   , CFWD  )
        CALL RDSREA ('CFLV'   , CFLV  )
        CALL RDSREA ('CFPD'   , CFPD  )
*       Root:shoot ratio
        CALL RDSREA ('RSSET'  , RSSET )
        CALL RDSREA ('RESF', RESF)
        CALL RDSREA ('TAU',  TAU)
        CALL RDSREA ('TAU2', TAU2)
        CALL RDSREA ('PGLA', PGLA)
        CALL RDSREA ('PGLB', PGLB)
*       Weight ratio of beans
        CALL RDSREA ('BEAPOD', BEAPOD)

*       Partitioning table
        CALL RDAREA ('FSHTB'  , FSHTB ,  ITABLE, IFSHN )
! Fraction shoot growth
        CALL RDAREA ('FWDTB'  , FWDTB ,  ITABLE, IFWDN )
! Fraction wood growth
        CALL RDAREA ('FLVTB'  , FLVTB ,  ITABLE, IFLVN )
! Fraction leaf

        CALL RDAREA ('FPDTB'  , FPDTB ,  ITABLE, IFPDN )
! Fraction pod growth

        CALL RDSREA ('FDRWD'  , FDRWD)
        CALL RDSREA ('FDRRT'  , FDRRT)
        CALL RDSREA ('FRSUPW', FRSUPW)
        CALL RDSREA ('PFRT', PFRT)
        CALL RDSREA ('PTRT', PTRT)
        CALL RDSREA ('MINCON', MINCON)
        CALL RDSREA ('HGHL'   , HGHL(1))
        CALL RDSREA ('HGHT'   , HGHT(1))

*       Shade tree characteristics
        CALL RDAREA ('TSLAIL', TSLAIL ,  ITABLE, ISLAIL )
        CALL RDAREA ('TSLAIT', TSLAIT ,  ITABLE, ISLAIT )
        CALL RDSREA ('SKDFL'  , KDF(2) )
        CALL RDSREA ('SKDFT'  , KS(2)  )
        CALL RDSREA ('SAMX'   , AMAX(2))
        CALL RDSREA ('SEFF'   , EFF(2) )
        CALL RDSREA ('SHGHL'  , HGHL(2) )
        CALL RDSREA ('SHGHT'  , HGHT(2) )

        AGE = AGEI


*       Initialize subroutines


     CALL  ROOT ( ITASK, DELT, NL, NLA, NLXM, NLBM, I1,
    &            TKL, CUMTKL, WCLQT, WCWPX, AGE,
    &            LTRT, WRT, WTFRT, WTRT ,WTFRTI,
    &            WTRTI, GTRT,
    &            AWURTT, AWURT, WSERT,
    &            DFRT, GFRT, WFRT)

     CALL WUPT ( ITASK, NLXM  , NL  , NLA   , NLBM,
```

```
     &          TKL    , WCLQT , WCWPX , WCFCX , WCSTX , AWURTT ,
     &          AWURT, ETRD  , ETAE  ,  EVSC  , TAI    ,
     &          TRWL   , PINT, PTRANS, ATRANS, PCEW   ,
     &          PENMAN, CROPF  )

      CALL LEAF (ITASK, DELT, AGEI, GLV, PCEW,
     &               WLVG, WLVI, DLV, LAI(1))

      CALL POD (ITASK, DELT,  TMAV,  GPD,
     &               WPD, WPDI, YIELD)

*        Close plant file
         CLOSE (IUNITD)

*        Initialize state variables
         WWDI =WWDI*NPL
         WWD    = WWDI

*        Dead biomass
         WLVD = 0.                                   !kg DM ha-1
         WWDD = 0.                                   !kg DM ha-1
         WTFRTD = 0.                                 !kg DM ha-1

*        Cumulated yield per year
         YYIELD = 0.                         !kgDM ha-1 on yearly basis

*        Actual yield in terms of fermented product
         ACYIEL = 0.                         !kg fermented cocoa ha-1

*        Weather data on a yearly basis
         YRDD    = 0.                        !J m-2 on yearly basis
         YRAIN   = 0.                        !mm water on yearly basis
         YTRANS = 0.                         !mm water on yearly basis

*        Total net CO2 assimilation
         TNASS = 0.                          !kg CO2 ha-1

*        Total dry matter increment
         TDM = 0.                            !kg DM ha-1

*        Weight of harvested pods
         WHAR   = 0.

*        variables for carbon balance check
         CHKDIF = 0.
         CHKIN   = 0.                        !kg C ha-1
         CHKFL   = 0.                        !kg C ha-1

*        leaf en trunk areas of cocoa and shade trees
         DO I1=2,INS
            LAI(I1) = 0.                          !m2 leaf m-2 soil
            SAI(I1) = 0.                          !m2 stem m-2 soil
         ENDDO
         TAI = 0.                                 !m2 plant area m-2 soil
         GAI = 0.                                 !m2 green leaves m2 soil

*        Miscellaneous state variables and reserves
         TADRW   = (WLVG + WWD + WPD) * (1.+ MINCON)        !kg DM ha-1
         TDRW    = TADRW + WRT * (1.+MINCON)                !kg DM ha-1
         WRES    = TDRW - (WLVG + WWD + WPD + WRT)          !kg DM ha-1
         MINRES = RESF * WRES                               !kg DM ha-1

*        Interpolate leaf and trunk area of the shade crop
         LAI(2) = LINT(TSLAIL, ISLAIL, AGEI)          !m2 leaf m-2 soil
         SAI(2) = LINT(TSLAIT, ISLAIT, AGEI)          !m2 stem m-2 soil

*        Calculate the Total and Green Area Index
         DO I1=1,INS
            TAI     = TAI + LAI(I1) + SAI(I1)    !m2 plant area m-2 soil
            GAI     = GAI + LAI(I1)              !m2 green leaf m-2 soil
         ENDDO

*        CO2 production factors
         CO2FRT  = 44./12. * (ASRQFRT*12./30. - CFFRT)
!kg CO2 kg-1 DM
         CO2TRT  = 44./12. * (ASRQTRT*12./30. - CFTRT)
         CO2WD   = 44./12. * (ASRQWD*12./30. - CFWD)
!kg CO2 kg-1 DM
         CO2LV   = 44./12. * (ASRQLV*12./30. - CFLV)
!kg CO2 kg-1 DM
         CO2PD   = 44./12. * (ASRQPD*12./30. - CFPD)
!kg CO2 kg-1 DM

         IDOYO  = IDOY                                !d


      ELSE IF (ITASK.EQ.2) THEN
*        ------------------------
*        Rate calculation section
*        ------------------------

         AGE = AGEI + TIME - STTIME

*        Weather data
*        Average temperature (TMAV) and day time average (TMAVD)
         TMAV   = 0.5 * (TMMX + TMMN)
         TMAVD = TMMX - 0.25 * (TMMX-TMMN)

         IF (TMAV.GT.40.) THEN
           WRITE (*,*) IYEAR,IDOY
           CALL FATALERR ('Av. Temp gt. 40.','case2')
         ENDIF
```

```
*       Transpiration and water uptake

      CALL  ROOT ( ITASK, DELT, NL, NLA, NLXM, NLBM, I1,
     &                   TKL, CUMTKL, WCLQT, WCWPX, AGE,
     &                  LTRT, WRT, WTFRT, WTRT,
     &                   WTFRTI,  WTRTI,  GTRT,
     &                 AWURTT, AWURT, WSERT,
     &                   DFRT,   GFRT, WFRT)

      CALL WUPT ( ITASK, NLXM  , NL  , NLA   , NLBM ,
     &            TKL   , WCLQT , WCWPX , WCFCX , WCSTX ,
     &            AWURTT ,
     &                 AWURT, ETRD  , ETAE  ,  EVSC  , TAI   ,
     &                 TRWL  ,  PINT, PTRANS, ATRANS, PCEW  ,
     &                   PENMAN, CROPF )

*       Carbohydrate production and respiration
*       Leaf CO2 assimilation
*       Interpolate the temperature correction for the maximum rate
*       of photosynthesis (AMAX(1)) from table (AMPTP)
        AMTMP   = LINT (AMTMPT, IAMTMN, TMAVD)
        AMAX(1) = AMX * AMTMP

        CALL TOTASC (IDOY, INS, LAT, RDD, FRPAR, KDF, KS,
     &               AMAX, EFF, LAI, SAI, HGHT, HGHL,
     &              FRABS, DTGA)

*       Carbohydrate production
        GPHOT = DTGA(1) * 30./44. * PCEW

*       Maintenance respiration
        MAINTS = MAINFRT*WTFRT + MAINTRT*WTRT*(1-FRSUPW)+
     &               MAINWD*WWD*(1-FRSUPW) + MAINLV*WLVG + MAINPD*WPD
        TEFF   = Q10**((TMAV - TREF)/10.)
        MAINT  = MAINTS * TEFF
        GRES   = GPHOT - MAINT


      IF ((LAI(1).LT.3.).AND.(AGE.GE.600.)) THEN
         FSH = 0.8
         FLV = 1.
         FWD = 0.
         FPD = 0.
       ELSE
*        Dry matter partitioning
         FSH     = LINT (FSHTB, IFSHN, AGE)
         FLV     = LINT (FLVTB, IFLVN, AGE)
         FWD     = LINT (FWDTB, IFWDN, AGE)
         FPD     = LINT (FPDTB, IFPDN, AGE)
       END IF

       FRT     = 1. - FSH
        FRTF    = PFRT * FRT
        TRTF    = PTRT * FRT

*       Assimilate requirements for growth
        ASRQ    = FSH * (ASRQWD*FWD + ASRQLV*FLV + ASRQPD*FPD) +
     &                  ASRQFRT*FRTF + ASRQTRT*TRTF
!  [kg CH2O kg-1 DM]

*       Growth takes only place when the reserves exceed the minimum
*       reserve concentration plus maintenace requirements
        IF (WRES .GT. MAINT*DELT + MINRES) THEN
          DRES =  (WRES - MINRES)/TAU
          GTW  = DRES / ASRQ
        ELSE
          DRES = 0.
          GTW  = 0.
        ENDIF

*       Growth of plant organs (and translocation)
        GWD     = FWD * FSH * GTW
        GLV     = FLV * FSH * GTW                 !  [kg DM ha-1 d-1]
        GPD     = FPD * FSH * GTW
        GRT     = FRT * GTW
        GTRT    = TRTF * GTW * WSERT(NLA)

*       Calculation of length of taproot, from known weight.
        QUOTIENT =  (WTRT * 1200)/(NPL * SW * PI)
        LTRT = QUOTIENT**0.3333

*       Growth rate of mass of taproot, per length of taproot
*(kg/ha/m)
        GMASS = SW * NPL * PI * (LTRT**2)/400

*       Growth rate of length per time (m/d)
        PGLTRT = PGLA * EXP(-PGLB*AGE)

*       Potential growth rate of taproot (kg/ha/d)
        PGTRT = GMASS * PGLTRT

*       Comparison between GTRT and PGTRT, because of negative
*       exponential behavior of growth of taproot.
        IF (GTRT.GT.PGTRT) THEN
          GTRT = PGTRT
        ELSE
          GTRT = GTRT
        END IF

*       Growth of fine roots
        TGFRT = MAX(0, GRT-GTRT)
        DO I1=1, NLA
           GFRT(I1)= TGFRT * WFRT(I1)/WTFRT * WSERT(I1)
```

```
      END DO

*     Death rate and netto growth rate of fine roots

      RSACT = WTFRT/TADRW
      IF (RSACT.GT.RSSET) THEN
          TDFRT = (WTFRT-RSSET*TADRW)/TAU2
      ELSE
          TDFRT = 0.
      END IF

      DO I1=1, NLA
         DFRT(I1)= TDFRT * WFRT(I1)/WTFRT
      END DO

*     Death rate of wood
      DWD = DLV/WLVG * WWD * FDRWD

        CALL LEAF (ITASK, DELT, AGE, GLV, PCEW,
     &               WLVG,WLVI,  DLV, LAI(1))

        CALL POD (ITASK, DELT, TMAV , GPD,
     &               WPD, WPDI,  YIELD)

*       Finish condtions
        IF (AGE  .GE.12500.) TERMNL = .TRUE.
        IF (WRES .LT.    0.) THEN
            CALL WARNING ('CASE2',' Reserves depleted')
            TERMNL = .TRUE.
        ENDIF
*       Output of

        IF (OUTPUT) THEN

*          States
           CALL OUTDAT (2, 0, 'DOY'    , DOY)
           CALL OUTDAT (2, 0, 'AGE'    , AGE)
           CALL OUTDAT (2, 0, 'TDM'    , TDM)
           CALL OUTDAT (2, 0, 'WRT'    , WRT)
           CALL OUTDAT (2, 0, 'WLVG'   , WLVG)
           CALL OUTDAT (2, 0, 'WLVD'   , WLVD)
           CALL OUTDAT (2, 0, 'WWD'    , WWD)
           CALL OUTDAT (2, 0, 'WWDD'   , WWDD)
           CALL OUTDAT (2, 0, 'WPD'    , WPD)
           CALL OUTDAT (2, 0, 'WHAR'   , WHAR)
           CALL OUTDAT (2, 0, 'WRES'   , WRES)
           CALL OUTDAT (2, 0, 'TNASS'  , TNASS)
           CALL OUTARR ('LAI'    , LAI, 1, INS)
           CALL OUTDAT (2, 0, 'TAI'    , TAI)
           CALL OUTDAT (2, 0, 'GAI'    , GAI)
           CALL OUTARR ('FRABS'  , FRABS, 1, INS)
           CALL OUTDAT (2, 0, 'TADRW'  , TADRW)
           CALL OUTDAT (2, 0, 'TDRW'   , TDRW)
           CALL OUTDAT (2, 0, 'HI'     , HI)
           call outdat (2,0,'flv', flv)
*       States from subroutine ROOT

           CALL OUTDAT (2,0, 'NLA', REAL(NLA))
           CALL OUTDAT (2,0, 'CUMTKL', CUMTKL)
           CALL OUTDAT (2,0, 'WRT', WRT)
           CALL OUTDAT (2,0, 'WTRT', WTRT)
           CALL OUTDAT (2, 0, 'WTFRT', WTFRT)
           CALL OUTARR ('WFRT', WFRT , 1, NLA)
           CALL OUTDAT (2,0, 'AWURTT', AWURTT)
           CALL OUTDAT (2,0, 'LTRT', LTRT)
           CALL OUTDAT (2,0, 'GTRT', GTRT)
           CALL OUTDAT (2,0, 'PGTRT', PGTRT)
           CALL OUTDAT (2,0, 'GFRT', GFRT)
           CALL OUTDAT (2,0, 'TGFRT', TGFRT)
           CALL OUTDAT (2,0, 'TDFRT', TDFRT)
           CALL OUTDAT (2,0, 'RSACT', RSACT)
           CALL OUTARR ('GFRT', GFRT, 1, NLA)
           CALL OUTARR ('WSERT', WSERT, 1, NLA)

*          Subroutine WUPT
           CALL OUTARR ('TRWL', TRWL, 1, NLA)
           CALL OUTDAT (2,0, 'PTRANS', PTRANS)
           CALL OUTDAT (2,0, 'ATRANS', ATRANS)


*          Driving variables and rates
           CALL OUTDAT (2, 0, 'RDD'    , RDD)
           CALL OUTDAT (2, 0, 'YRDD'   , YRDD)
           CALL OUTDAT (2, 0, 'TMAV'   , TMAV)
           CALL OUTDAT (2, 0, 'TMAVD'  , TMAVD)
           CALL OUTDAT (2, 0, 'GPHOT'  , GPHOT)
           CALL OUTDAT (2, 0, 'MAINT'  , MAINT)
           CALL OUTDAT (2, 0, 'GRES'   , GRES)
           CALL OUTDAT (2, 0, 'DRES'   , DRES)
           CALL OUTDAT (2, 0, 'MINRES' , MINRES)
           CALL OUTDAT (2, 0, 'ASRQ'   , ASRQ)
           CALL OUTDAT (2, 0, 'GTW'    , GTW)
           CALL OUTDAT (2, 0, 'DTW'    , DTW)
           CALL OUTDAT (2, 0, 'GRT'    , GRT)
           CALL OUTDAT (2, 0, 'GWD'    , GWD)
           CALL OUTDAT (2, 0, 'DWD'    , DWD)
           CALL OUTDAT (2, 0, 'GLV'    , GLV)
           CALL OUTDAT (2, 0, 'DLV'    , DLV)
           CALL OUTDAT (2, 0, 'GPD'    , GPD)
           CALL OUTDAT (2, 0, 'YIELD'  , YIELD)
           CALL OUTDAT (2, 0, 'YYIELD', YYIELD)
           CALL OUTDAT (2, 0, 'ACYIEL', ACYIEL)
           CALL OUTDAT (2, 0, 'TRANSL', TRANSL)
```

```
         CALL OUTDAT (2, 0, 'CHKIN'  , CHKIN)
         CALL OUTDAT (2, 0, 'CHKFL'  , CHKFL)
         CALL OUTDAT (2, 0, 'CHKDIF', CHKDIF)
         CALL OUTDAT (2, 0, 'CHKLV'  , CHKLV)
         CALL OUTDAT (2, 0, 'CHKWD'  , CHKWD)
         CALL OUTDAT (2, 0, 'CHKRT'  , CHKRT)
         CALL OUTDAT (2, 0, 'CHKPD'  , CHKPD)
         CALL OUTDAT (2, 0, 'CHKFRT'  , CHKFRT)
         CALL OUTDAT (2, 0, 'CHKTRT'  , CHKTRT)

         CALL OUTDAT (2, 0, 'TFALL'  , TFALL)
         CALL OUTDAT (2, 0, 'STEMFL', STEMFL)
         CALL OUTDAT (2, 0, 'PINT'   , PINT)
         CALL OUTDAT (2, 0, 'PCEW'   , PCEW)
*        CALL OUTDAT (2, 0, 'VPD', VPD)
         CALL OUTDAT (2, 0, 'ETRD'   , ETRD)
         CALL OUTDAT (2, 0, 'ETAE'   , ETAE)
         CALL OUTDAT (2, 0, 'PENMAN', PENMAN)
         CALL OUTDAT (2, 0, 'CROPF'  , CROPF)
         CALL OUTDAT (2, 0, 'YRAIN'  , YRAIN)
         CALL OUTDAT (2, 0, 'YTRANS', YTRANS)
       END IF

      ELSE IF (ITASK.EQ.3) THEN
*       -------------------
*       Integration section
*       -------------------


        CALL  ROOT ( ITASK, DELT, NL, NLA, NLXM, NLBM, I1,
     &                   TKL, CUMTKL, WCLQT, WCWPX, AGE,
     &                LTRT, WRT, WTFRT, WTRT,WTFRTI, WTRTI,  GTRT,
     &                 AWURTT, AWURT, WSERT,
     &                   DFRT, GFRT, WFRT)

        CALL LEAF (ITASK, DELT, AGE, GLV, PCEW,
     &              WLVG,WLVI, DLV, LAI(1))

        CALL POD (ITASK, DELT, TMAV , GPD,
     &              WPD, WPDI, YIELD)

*       Dry matter production
        TDM     = INTGRL (TDM , GTW, DELT)
        WLVG    = INTGRL (WLVG, GLV-DLV, DELT)
        WLVD    = INTGRL (WLVD, DLV , DELT)
        WWD     = INTGRL (WWD , GWD-DWD, DELT)
        WWDD    = INTGRL (WWDD, DWD , DELT)
        WPD     = INTGRL (WPD , GPD-YIELD, DELT)
        WTFRTD = INTGRL (WTFRTD , TDFRT, DELT)
        WHAR    = INTGRL (WHAR, YIELD, DELT)
        YYIELD = INTGRL (YYIELD, YIELD, DELT)
        WRES    = INTGRL (WRES, GRES-DRES, DELT)
```

```
        YRAIN  = INTGRL (yrain, rain, delt)
        YRDD   = INTGRL (YRDD, RDD, DELT)
        YTRANS = INTGRL (ytrans, penman, delt)

*       ACtual YIELd is determined by YYIELD (in kg DM ha-1),the
*       beans/pod ratio (BEAPOD),a factor of loss because of the
*       fermentation process and a factor which accounts for the
*       commercial watercontent of 7%.

        ACYIEL = YYIELD*BEAPOD*0.95*1.07     !kg fermented beans ha-1

        IF (IDOY .EQ. IDOYO) YYIELD = 0.
*        IF (IDOY .EQ. IDOYO) ECIELD = 0.
        IF (IDOY .EQ. IDOYO) Yrain  = 0.
        IF (IDOY .EQ. IDOYO) Ytrans = 0.
        IF (IDOY .EQ. IDOYO) YRDD   = 0.

*       Operations on state variables
        TADRW  = WWD   + WLVG  + WPD
        TDRW   = TADRW + WRT + WRES
        HI     = WHAR / NOTNUL(GTW)
        MINRES = RESF * MINCON*(TDRW - WRES)

*       Shade leaf area, shade stem area
        LAI(2) = LINT( TSLAIL, ISLAIL, AGE )
        SAI(2) = LINT( TSLAIT, ISLAIT, AGE )

*       Calculate the Total and Green Area Index
        TAI = 0.
        GAI = 0.
        DO I1=1,INS
           TAI    = TAI + LAI(I1) + SAI(I1)
           GAI    = GAI + LAI(I1)
        ENDDO



*       Carbon balance check
        TNASS  = INTGRL (TNASS,((GPHOT - MAINT - GRES +
     &                  DRES)*44./30.)-
     &                 (TGFRT*CO2FRT + GTRT*CO2TRT + GLV*CO2LV +
     &                 GWD*CO2WD + GPD*CO2PD),DELT)
        CHKFL  = TNASS * (12./44.)
        CHKIN  = (WLVG + WLVD - WLVI)*CFLV + (WWD + WWDD - WWDI)*CFWD
     &         + (WTRT - WTRTI)*CFTRT + (WTFRT + WTFRTD -
     &          WTFRTI)*CFFRT
     &                 + (WPD + WHAR - WPDI)*CFPD
        CHKDIF = (CHKIN-CHKFL)/NOTNUL(CHKIN)

      CHKLV = GLV*CFLV + GLV*CO2LV*12./44. - GLV*ASRQLV*12./30.
      CHKWD = GWD*CFWD + GWD*CO2WD*12./44. - GWD*ASRQWD*12./30.
      CHKFRT = TGFRT*CFFRT + TGFRT*CO2FRT*12./44.-
```

```
&               TGFRT*ASRQFRT*12./30.
      CHKTRT = GTRT*CFTRT + GTRT*CO2TRT*12./44.- GTRT*ASRQTRT*12./30.
      CHKPD = GPD*CFPD + GPD*CO2PD*12./44. - GPD*ASRQPD*12./30.

      ELSE IF (ITASK.EQ.4) THEN
*       ----------------
*       Terminal section
*       ----------------
*       No tasks defined for terminal section


      END IF

      RETURN
      END


*     Subroutines

*----------------------------------------------------------------*
* SUBROUTINE LEAF
*
* Authors: Wouter Gerritsma
*
* Date    : May 1995
*
* Purpose: This subroutine simulates leaf growth and senescence of
*
*          leaf age classes based on the boxcar train without
*
*          dispersion delay techinque
*           *
*
*
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
*
* name   type meaning                                  units
class *
* ----   ---- -------                                  -----  ----
- *
* ITASK   I4  Task that subroutine should perform         -      I
*
* AGE     R4  Age of trees                                d      I
*
* GLV     R4  Growth rate of leaves                    kg ha-1  I
*
* PCEW    R4  Factor that accounts for reduced
*
*             photosynthesis due to water stress          -      I
*
* WLVG    R4  Weight of leaves                         kg ha-1  O
*
* DLV     R4  Death rate of leaves                     kg ha-1  O
*
* LAI     R4  Leaf Area Index                          m2 m-2   O
*
*
*
* FATAL ERROR CHECKS (execution terminated, message)
*
* condition: if maximumn leaf age greater than 1 year, minimum leaf
*
*           leaf age less than zero, maximum less than minmum.
*
*
*
* SUBROUTINES and FUNCTIONS called : ERROR, RDSREA, RDAREA from
* TTUTIL
* FILE usage :
*
*----------------------------------------------------------------*
      SUBROUTINE LEAF (ITASK, DELT, AGE, GLV, PCEW,
     &                 WLVG, WLVI, DLV, LAI)

      IMPLICIT REAL (A-Z)

*     Formal parameters
      INTEGER ITASK

      REAL DELT, AGE, GLV, WLVG,WLVI, DLV, PCEW, LAI

*     Standard local declarations
      REAL WEIGHT(0:365), LA(0:365)
      INTEGER ITABLE, I1, ILD, IPLD

      PARAMETER (ITABLE = 100)

      REAL      FSLATB(ITABLE)
      INTEGER   IFSLAN



      IF (ITASK.EQ.1) THEN
*       ---------------------
*       Initialization section
*       ---------------------

        CALL RDSREA ('NPL'   , NPL   )              ! [tree-1 ha-1]
        CALL RDSREA ('WLVI'  , WLVI  )              ! [kg DM tree-1]
        CALL RDSREA ('MAXLAG', MAXLAG)              ! [days]
        CALL RDSREA ('MINLAG', MINLAG)              ! [days]
        CALL RDAREA ('FSLATB', FSLATB,  ITABLE, IFSLAN)
        IPLD = INT(MAXLAG)                          ! [-]
        WLVI = WLVI * NPL
```

```
      WLVG = WLVI
      SLA  = LINT (FSLATB, IFSLAN, AGE)          ! [ha kg-1]

*     Initialize boxcar train with leaf weights and leaf areas
      LAI   = 0.
      DO 10 I1 = 1,IPLD
        WEIGHT(I1)  = WLVG/MAXLAG
        LA(I1)      = WEIGHT(I1) * SLA
        LAI         = LAI + LA(I1)
10    CONTINUE

*     Fatal error checks
      IF (MAXLAG.GT.365.) CALL FATALERR
     &           ('LEAF','Maximum leaf age greater than one year')

      IF (MINLAG.LT.0.) CALL FATALERR
     &          ('LEAF','Minimum leaf age less than zero (0)')

      IF (MAXLAG.LT.MINLAG) CALL FATALERR
     &      ('LEAF','Maximum leaf age less than mininum leaf age')

     ELSE IF (ITASK.EQ.2) THEN
*     ------------------------
*     Rate calculation section
*     ------------------------
      SLA = LINT (FSLATB, IFSLAN, AGE)              ! [ha kg-1]

*     Growth rate leaves
      WEIGHT(0) = GLV*DELT
      LA(0)     = WEIGHT(0)*SLA

*     Adjust leaf age for water stress sensitivity
      ILD    = NINT(MINLAG - PCEW*MINLAG + PCEW*MAXLAG)

*     Death rate leaves
      DLV = 0.
      IF (ILD.LT.IPLD) THEN
        DO 20, I1=ILD,IPLD
          DLV        = DLV + WEIGHT(I1)/DELT
          LA(I1) = 0.
          WEIGHT(I1) = 0.
20       CONTINUE
      ELSEIF (ILD.EQ.IPLD) THEN
        DLV        = WEIGHT(ILD)/DELT
        WEIGHT(ILD) = 0.
        LA(ILD) = 0.
      ELSEIF (ILD.GT.IPLD) THEN
        DLV = 0.
      ENDIF

     ELSE IF (ITASK.EQ.3) THEN
*     ------------------------
*     Integration section
*     ------------------------
*     Shift all the leaves, weight and areas one class
      LAI = 0.
      DO 30 I1=ILD-1,0,-1
        WEIGHT(I1+1) = WEIGHT(I1)
        LA(I1+1)     = LA(I1)
        LAI          = LAI + LA(I1)              ! [m2 leaf ha-1]
30    CONTINUE
      WEIGHT(0) = 0.
      LA(0)     = 0.

*     reset IPLD
      IPLD = ILD

    END IF
    RETURN
    END

*------------------------------------------------------------*
* SUBROUTINE ROOT
*
*
*
* Author(s): Liesje Mommer
*
* Date     : oktober 1998, Version:1.0
*
* Purposes:
*
* To calculate the number of layers of which water can be taken up
*
* To calculate the root biomass of cacao, separated in three classes:
*
* finest roots, able to take up water; other fine roots; taproot.
*
* To calculate the distribution of the fine roots in the soil.
*
* To calculate the rootlet surface within a layer.
*
```

```
*
*
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
*
* name   type meaning (unit)
class *
* ----   ---- ---------------                                   ----
- *
* PLTMOD  C*  Name of plant module (-)                             ?
*
* ITASK   I4  Task that subroutine should perform (-)              I
*
* IUNITD  I4  Unit number that is used for input files (-)         ?
*
* IUNITO  I4  Unit number that is used for output file (-)         ?
*
* IUNITL  I4  Unit number that is used for log file (-)            ?
*
* FILEP   C*  File name with which plant parameters are read (-)   ?
*
* OUTPUT  L4  Flag to indicate if output should be done (-)        ?
*
* TERMNL  L4  Flag to indicate if simulation is to stop (-)        ?
*
* DOY     R4  Day number since 1 January (day of year) (d)         ?
*
* IDOY    I4  Day number within year of simulation (d)             ?
*
* IYEAR   I4  Year of simulation (y)                               ?
*
* DELT    R4  Time interval of integration (d)                     I
*
* STTIME  R4  Start time of simulation (d)                         ?
*
* TIME    R4  Time of simulation (d)                               ?
*
* NL      I4  Actual number of soil compartments (-)               I
*
* I1      I4  DO-loop counter (<not given>)                        I
*
* TKL     R4  Thicknesses of soil compartments (m)                 I
*
* AGE     R4  Age of tree (d)                                      I
*
* WRES    R4  Weight of reserves (kg CH2O ha-1)                    I
*
*----------------------------------------------------------------------

SUBROUTINE ROOT ( ITASK, DELT, NL, NLA, NLXM, NLBM, I1,
     &                  TKL, CUMTKL, WCLQT, WCWPX, AGE,
     &               LTRT, WRT, WTFRT, WTRT, WTFRTI, WTRTI, GTRT,
     &                AWURTT, AWURT, WSERT,
     &                    DFRT, GFRT, WFRT)

      IMPLICIT NONE

*     Formal parameters
      INTEGER ITASK
      REAL DELT
      INTEGER NL, NLA, NLXM, NLBM, I1
      REAL AGE, WRT , LTRT
      REAL WTFRT, WTRT
      REAL WTFRTI, WTRTI
      REAL AWURTT
      REAL GTRT, CUMTKL
      REAL AWURT(NLBM)
      REAL GFRT(NLBM), DFRT (NLBM), WFRT(NLBM)
      REAL WSERT(NLBM)
      REAL TKL(NLXM), WCLQT(NLXM), WCWPX(NLXM)

*     Local declarations

*     Plant parameters
      REAL NPL, AGEI

*     Fine root declarations
*     Length of roots able to take up water
      REAL LWURT

*     Maximum fine roots depends on age
      REAL WMAX                                  !kg DM ha-1

*     Cumulative rooting depth
      REAL CUMTK2                                !m

*     Fraction finest roots of all lateral roots, able to take up
*     water, diameter less then 2 mm.
      REAL FFRT                                  !-

*     Mean diameter and specific root length of the finest root
*     classes (0-1mm and 1-2mm).
      REAL DIAM1, DIAM2, SPRTL1, SPRTL2

*     Specific weight of wood
      REAL SW                                    !kg m-3

*     Length and diameter of taproot, suffix 1 and 2 determine
*     whether x is AGE or AGE-DELT, respectively.
      REAL LTRTI

*     Weight of taproot and total root weight
*      REAL WTRTI, WTFRTI
```

```
*       Parameter pi
        REAL PI
        PARAMETER (PI= 3.1415927)

        REAL ZERO
        PARAMETER (ZERO=0.)

*       Array declaratie
        INTEGER NLRT
        PARAMETER (NLRT=10)
        REAL WFRTI(1:NLRT),  WWURT(1:NLRT)
        REAL LWURT1(1:NLRT), LWURT2(1:NLRT)

*       Function table declaration
*       Variable ITABLE gives the maximum length of the array, variable
*       LTRMN counts the actual number of classes in the array.
*       The table LTRTB gives the Length of the TapRooT with age.
        INTEGER ITABLE
        PARAMETER (ITABLE = 10)

        REAL LTRTB(ITABLE)
        INTEGER LTRTMN

*       The table MXFRTB gives the MaXimum Fine Root weight per age
        REAL  WMAXTB (ITABLE)
        INTEGER WMAXMN

*       TTUTIL functions
        REAL INTGRL, LINT

        IF (ITASK.EQ.1) THEN
*       ---------------------
*       Initialisation section
*       ---------------------

**       Read plant parameters from file
        CALL RDSREA ('NPL', NPL)
        CALL RDAREA ('LTRTB', LTRTB, ITABLE, LTRTMN)
        CALL RDAREA ('WMAXTB', WMAXTB, ITABLE, WMAXMN)
        CALL RDSREA ('FFRT', FFRT)
        CALL RDSREA ('SW', SW)
        CALL RDSREA ('DIAM1', DIAM1)
        CALL RDSREA ('DIAM2', DIAM2)
        CALL RDSREA ('SPRTL1', SPRTL1)
        CALL RDSREA ('SPRTL2',SPRTL2)

        NLA     = 0
        CUMTKL  = 0.
        CUMTK2  = 0.
        WTRT    = 0.
        WRT     = 0.
        LWURT   = 0.
        AWURTT  = 0.
        WTFRT   = 0.

*        Arrays are set to zero.
         DO I1=1, NLXM
            GFRT(I1)    = 0.
            DFRT(I1)    = 0.
            WWURT(I1)   = 0.
            LWURT1(I1)  = 0.
            LWURT2(I1)  = 0.
         END DO

         DO I1=1, NLBM
            WFRT(I1) = 0.
            AWURT(I1) = 0.
         END DO

*       Initialize tap root, assuming a cone
        LTRTI = LINT (LTRTB, LTRTMN, AGE)
        WTRTI = (PI*(LTRTI/20.)**2.)/3. * LTRTI * SW * NPL
*       kg DM ha-1 = [m3 plant-1] [kg m-3] [ plant ha-1]

        LTRT = LTRTI
        WTRT = WTRTI


*       Number of layers of which water can be taken up depends on
*       length of taproot

        DO I1 = 1, NL

            IF (LTRT.GT.CUMTKL) THEN
                NLA = NLA + 1
                CUMTKL = CUMTKL + TKL(I1)
            ELSE
                NLA = NLA
            ENDIF
        END DO

        WMAX = LINT (WMAXTB, WMAXMN, AGE)



*       Initialise array of fine roots. CUMTKL is used as an
*       intermediate variable and will be used as an intermediate
*       variable again, will be set to zero again.

          CUMTKL = 0.

          DO I1=1, NLA

        CUMTK2 = CUMTKL
```

```
      CUMTKL = CUMTKL + TKL(I1)
      WFRTI(I1)= WMAX * (-1./9.0) * EXP(-9.0*CUMTKL) -
     &               WMAX * (-1./9.0) * EXP(-9.0*CUMTK2)

      WFRT(I1) = WFRTI(I1)

      WTFRTI = WTFRTI + WFRT(I1)
      WTFRT  = WTFRTI
      END DO

      WRT = WTRT + WTFRT

      ELSE IF (ITASK.EQ.2) THEN
*     ------------------------
*     Rate calculation section
*     ------------------------

*      Number of soil layers in project
      DO I1 = NLA, NL
      IF (LTRT.GT.CUMTKL) THEN
              NLA = NLA + 1
              CUMTKL = CUMTKL + TKL(I1)
              WFRT(NLA) = WTRTI
              ELSE
              NLA = NLA
          ENDIF
      END DO


      DO I1=1, NLA
          WSERT(I1) = 1.
              IF (WCLQT(I1).LT.WCWPX(I1)) THEN
              WSERT(I1) = 0.
              END IF
      END DO




*     biomass of roots able to take up water
      DO I1=1, NLA
          WWURT(I1) = FFRT * WFRT(I1)
      END DO

*
      LWURT=0.
      DO I1=1,NLA
          LWURT1(I1) = 0.5 * WWURT(I1) * SPRTL1
          LWURT2(I1) = 0.5 * WWURT(I1) * SPRTL2
          LWURT = LWURT + LWURT1(I1) + LWURT2(I1)
      END DO

      AWURTT=0.
      DO I1=1, NLA
          AWURT(I1) = (PI*DIAM1)*LWURT1(I1)+
     &                          (PI*DIAM2)*LWURT2(I1)
          AWURTT = AWURTT + AWURT(I1)
      END DO


      ELSE IF (ITASK.EQ.3) THEN
*     -------------------
*     Integration section
*     -------------------
*     biomass of fine roots
      DO I1 =1, NLA
          WFRT(I1)  = INTGRL (WFRT(I1), GFRT(I1)-DFRT(I1), DELT)
      END DO

*     biomass of taproot
      WTRT = INTGRL(WTRT, GTRT, DELT)

*     operation on state variables, calculating total root biomass.
      WTFRT = 0.
      DO I1=1, NLA
        WTFRT = WTFRT + WFRT(I1)
      END DO

      WRT = WTFRT + WTRT

      END IF

      RETURN

      END

*----------------------------------------------------------------------*
* SUBROUTINE WUPT
*
*
*
* Author : Wouter Gerritsma & Liesje Mommer
*
* Date   : March 1999
*
* Version: 1.0
*
*
*
* Purpose: Calculate potential and actual transpiration, and water
*          water uptake from the separate soil layers.
*
*
*
```

```
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
*
* name   type meaning                                    units class
*
---- -------                                              ----  --- *
* ITASK   I4  Task that subroutine should perform          -     I
*
* NLXM    I4  no. of layers as declared in calling program -     I
*
* NL      I4  number of layers specified in input file     -     I
*
* TKL[]   R4  thickness of soil compartments               m     I
*
* WCLQT[] R4  volumetric soil water content per layer      -     I
*
* WCWPX[] R4  volumetric water content at wilting point    -     I
*
* WCFCX[] R4  volumetric water content at field capacity   -     I
*
* WCSTX[] R4  volumetric water content at saturation       -     I
*
* ETRD    R4  Radiation driven part of ETPMD               mm/d  I
*
* ETAE    R4  Dryness driven part of ETPMD                 mm/d  I
*
* RAIN    R4  Daily amount of rainfall                     mm/d  I
*
* EVSC    R4  actual (realized) evaporation rate           mm/d  I
*
* TAI     R4  total 'leaf' area index                      -     I
*
* ZRT     R4  rooted depth                                 -     I
*
* TRWL[]  R4  Actual transpiration rate per layer          mm/d  O
*
* RAINS   R4  daily amount of rainfall reaching the soil   mm/d  O
*
* PTRANS  R4  Potential transpiration rate                 mm/d  O
*
* ATRANS  R4  Actual transpiration rate                    mm/d  O
*
* PCEW    R4  Factor that accounts for reduced
*
*             photosynthesis due to water stress           -     O
*
* PENMAN  R4  Penman reference value for potential
*
*             evapotranspiration                           mm/d  O
*
* CROPF   R4  Crop factor for crop water requirement       -     O
*
* WSERT2  R4  Auxiliary variable to calculate root extension -     O
*
*
*
*
*
* Fatal error checks: if NL > NLLM
*
* Warnings           : none
*
* Subprograms called: SWSE, many from TTUTIL
*
* File usage         : FILEP
*
*------------------------------------------------------------------*
      SUBROUTINE WUPT ( ITASK, NLXM   , NL   , NLA     , NLBM ,
     &                  TKL    , WCLQT , WCWPX , WCFCX , WCSTX ,
     &                  AWURTT ,
     &                  AWURT, ETRD   , ETAE   ,  EVSC   , TAI    ,
     &                  TRWL   , PINT, PTRANS, ATRANS, PCEW ,
     &                        PENMAN,  CROPF )

      IMPLICIT NONE

*     Formal parameters

      INTEGER ITASK

      INTEGER NLXM, NL, NLA , NLBM
      REAL TRWL(NLXM)  , TKL(NLXM)
      REAL WCLQT(NLXM), WCWPX(NLXM), WCFCX(NLXM), WCSTX(NLXM)

      REAL AWURTT
      REAL AWURT(NLBM)
      REAL EVSC, ETRD, ETAE, PTRANS, ATRANS, PCEW
      REAL  PINT, TAI, PENMAN, CROPF

*      LOGICAL OUTPUT
*      CHARACTER FILEP*80
*      REAL LINT

*     Local declarations
      INTEGER NLLM1
      PARAMETER (NLLM1=10)
      REAL WSEL(NLLM1)

      INTEGER I1

*     REAL TFALL, STEMFL, TFALA, TFALB, STFLA, STFLB
      REAL TRANSC, WCWET, AVAIL, PRWU , P

      REAL LIMIT
```

```
      SAVE

      IF (NL .GT. NLBM) CALL FATALERR
     &   ('CASE2','too many layers in external arrays')

      IF (ITASK .EQ. 1) THEN
*       ----------------------
*       Initialization section
*       ----------------------

*     Initialize input file
*      CALL RDINIT (IUNITD, IUNITL, FILEP)


*       Stemflow and troughfall parameters
*        CALL RDSREA ('TFALA'  , TFALA  )
*        CALL RDSREA ('TFALB'  , TFALB  )
*        CALL RDSREA ('STFLA'  , STFLA  )
*        CALL RDSREA ('STFLB'  , STFLB  )

        CALL RDSREA ('TRANSC', TRANSC)
        CALL RDSREA ('WCWET' , WCWET )

*      CLOSE (IUNITD)

*       Transpiration rate per layer is 'zeroed'
        DO 20 I1=1,NL
           TRWL(I1) = 0.
20      CONTINUE


      ELSE IF (ITASK.EQ.2) THEN
*       ------------------------
*       Rate calculation section
*       ------------------------

*       Troughfall (TFALL), Stemflow (STFLOW) and
*       Rainfall interception (PINT)
*        TFALL    = LIMIT (0., RAIN, TFALA*RAIN + TFALB)
! [mm d-1]
*        STEMFL   = LIMIT (0., RAIN, STFLA*RAIN + STFLB)
! [mm d-1]
*        PINT     = MAX(0.,RAIN - TFALL - STEMFL)
! [mm d-1]

*       Rainfall reaching the soil (RAINS)(= TFALL + STEMFL)
*        RAINS    = RAIN-PINT
! [mm d-1]

*       Transpiration and water uptake
*       Potential transpiration
*         PTRANS = MAX(0.,(ETRD + ETAE - 0.5*PINT))
        PTRANS = MAX(0.,(ETRD*(1.-EXP(-0.5*TAI)) + ETAE*MIN(2.0, TAI)
     &                  - 0.5*PINT))                        ! [mm d-1]

*       Potential water uptake rate and Soil water depletion factor.
        PRWU = MAX (0., PTRANS / AWURTT)
        P    = TRANSC / (TRANSC + PTRANS)

*       calculate actual transpiration (ATRANS) from
        ATRANS = 0.
        DO 50 I1 = 1, NLA
          CALL SWSE (WCLQT(I1), P, WCWET, WCWPX(I1), WCFCX(I1),
     &               WCSTX(I1), WSEL(I1))
          TRWL(I1) = PRWU * WSEL(I1) * AWURT(I1)
          AVAIL = MAX(0., (WCLQT(I1) - WCWPX(I1)) * TKL(I1) * 1000.)
          IF (TRWL(I1) .GT. AVAIL) TRWL(I1) = AVAIL
          ATRANS = ATRANS + ABS(TRWL(I1))
50      CONTINUE

*       Calculate growth reduction due to waterstress
        IF (PTRANS.GT.0.) THEN
          PCEW = ATRANS/PTRANS
        ELSE
          ATRANS = 0.
          PCEW   = 1.
        END IF

*        WSERT = 1.
*        IF (WCLQT(IRGL).LT.WCWPX(IRGL)) WSERT = 0.

*       Miscellaneous water related variables
        CROPF  = (PTRANS+EVSC)/(ETRD+ETAE)
        PENMAN = ETRD+ETAE

      END IF
      RETURN
      END


*-----------------------------------------------------------------------
--*
* SUBROUTINE POD
*
* Authors: Wouter Gerritsma
*
* Date   : May 1995
*
* Purpose: This subroutine simulates pod growth and development

* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
*
```

```
* name    type meaning                                   units class
*
* ----    ---- -------                                   -----  ---*
* ITASK    I4  Task that subroutine should perform         -      I
*
* TMAV     R4  Daily Average Temperature                 degree   I
*
* GPD      R4  Growth rate of pods                 kg DM ha-1 d-1 I
*
* WPD      R4  Weight of pods                         kg DM ha-1  O
*
* YIELD    R4  Weight of harvested pods            kg DM ha-1 d-1 O
*
*
*
* FATAL ERROR CHECKS (execution terminated, message)
*
* condition:
*
*
*
* SUBROUTINES and FUNCTIONS called :
*
* FILE usage :
*
*
*
*------------------------------------------------------------------
--*
      SUBROUTINE POD (ITASK, DELT, TMAV , GPD,
     &                  WPD,WPDI, YIELD)

      IMPLICIT REAL (A-Z)

*     Formal parameters

      INTEGER ITASK

      REAL WPD, WPDI, GPD, YIELD

*     Standard local declarations
      REAL    WPOD(0:200), STAGE(0:200),SS(200),GPOD(0:200)
      INTEGER ITABLE, I1, IPOD
      LOGICAL INIT

      PARAMETER (ITABLE = 100)

      REAL      SSTB(ITABLE)
      INTEGER   ISSN

      DATA INIT /.FALSE./

      IF (ITASK.EQ.1) THEN
*       ---------------------
*       Initialization section
*       ---------------------

        CALL RDSREA ('NPL'   , NPL   )               ! [tree-1 ha-1]
        CALL RDSREA ('WPDI'  , WPDI  )               ! [kg DM tree-
1]
        CALL RDAREA ('SSTB'  , SSTB  ,  ITABLE, ISSN )

        WPDI = WPDI * NPL
        WPD = WPDI

*       Initialize stage distributions
        TSS = 0.
        DO 10 I1 = 1,200
          STAGE(I1) = 0.00154 + 2.048E-4 * 27. * I1
          WPOD(I1)  = 0.
          GPOD(I1)  = 0.
          SS(I1)    = 0.
          IF (STAGE(I1).LT.1.) THEN
            SS(I1)  = LINT(SSTB,ISSN,STAGE(I1))
            TSS = TSS + SS(I1)
            IPOD = I1
          ELSEIF ((STAGE(I1).GE.1.).AND.(INIT.EQV..FALSE.)) THEN
            INIT = .TRUE.
            STAGE(I1) = 0.
          ENDIF
10      CONTINUE

*       Initialize boxcar train with pod weights
        WPD = 0.
        DO 20 I1 = 1,IPOD
          WPOD(I1) = WPDI * SS(I1)/TSS
          WPD      = WPD + WPOD(I1)
20      CONTINUE

*       Error check on initialization
        IF( ABS(WPD-WPDI).GT.0.001 ) CALL FATALERR ('POD',
     &            'Error during initialization of pod weights')

      ELSE IF (ITASK.EQ.2) THEN
*       -----------------------
*       Rate calculation section
*       -----------------------
*       Development rate
        DEVRH = MAX(0., 0.00154 + 2.048E-4 * TMAV)
        DEVRL = MAX(0.,-0.00226 + 3.600E-4 * TMAV)
        DEVR  = MIN(DEVRL,DEVRH)

*       Growth per unit sink strength
        PGRUSS = GPD/TSS
```

```
*       Growth rate of pods per class
        DO 40 I1 = 1,IPOD
          IF (SS(I1) .GT. 0.) THEN
            GPOD(I1) = SS(I1)*PGRUSS
          ELSE
            GPOD(I1) = 0.
          ENDIF
40      CONTINUE

*       Initialize the first boxcars
        IF (GPD.GT.0.) THEN
          STAGE(0) = DEVR
          WPOD(0)  = 0.
          GPOD(0)  = 0.
        ELSE
          STAGE(0) = 0.
          WPOD(0)  = 0.
          GPOD(0)  = 0.
        ENDIF

      ELSE IF (ITASK.EQ.3) THEN
*       ------------------------
*       Integration section
*       ------------------------
        TSS   = 0.
        YIELD = 0.
        DO 30 I1 = IPOD+1,1,-1
          IF (STAGE(I1).GT.1.) THEN
            YIELD = YIELD + WPOD(I1)+GPOD(I1)
            WPOD(I1+1)  = 0.
            STAGE(I1+1) = 0.
            IPOD = I1
          ELSE
            WPOD(I1+1)  = WPOD(I1) + GPOD(I1)
            STAGE(I1+1) = STAGE(I1)+ DEVR
            SS(I1+1)    = LINT(SSTB,ISSN,STAGE(I1))
            TSS         = TSS + SS(I1+1)
          ENDIF
30      CONTINUE
      ENDIF

      RETURN
      END
```

Subroutine setpmd

```
*-----------------------------------------------------------------
* SUBROUTINE SETPMD (Subroutine Evap. Trans. PenMan Daily)
*
* Authors: Daniel van Kraalingen & Liesje Mommer
*
* Date   :  january 1999
*
* Version: 1.1
*
 Purpose: This subroutine calculates reference evapotranspiration
          in a manner similar to Penman (1948). To obtain crop
          evapotranspiration, multiplication with a Penman crop
          factor should be done. Calculations can be carried out for
          three types of surfaces: water, wet soil, and short grass
          (ISURF=1,2,3 resp.). When the input variable TMDI is set to
          zero, a single calculation is done and an estimate is
          provided of temperature difference between the environment
          and the surface (DT). If the absolute value of DT is large
          an iterative Penman can be carried out which continue until
          the new surface temperature differs by no more than TMDI
          from the old surface temperature. Two types of long-   wave
          radiation calculations are available Swinbank and Brunt.
          The switch between the two is made by choosing the right
          values for ANGA and ANGB. If ANGA and ANGB are zero,
          Swinbank is used, if both are positive, Brunt is used and
          the ANGA and ANGB values are in the calculation of the
          cloud cover.
 Refs.  : Kraalingen, D.W.G. van, W. Stol, 1997. Evapotranspiration
          modules for crop growth simulation. Quantitative Approaches
          in Systems Analysis No. 11. DLO Research Institute for
          Agrobiology and Soil Fertility (AB-DLO), The C.T. de Wit
          graduate school for Production Ecology (PE). Wageningen.
          The Netherlands.

*
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
*
* name   type meaning (units)                                    ----
* ----   ---- ---------------
* IDOY    I4  Day number within year of simulation (d)              I
*
* LAT     R4  Latitude of site (dec.degr.)                          I
*
* ISURF   I4  Switch value to choose between different surface
*
*             types (-)                                             I
*
* RF      R4  Reflection (=albedo) of surface (-)                   I
*
* ANGA    R4  A value of Angstrom formula (-)                       I
*
* ANGB    R4  B value of Angstrom formula (-)                       I
*
* TMDI    R4  Temperature tolerance (switches between single and
*
*             iterative Penman) (-)                                 I
*
* RDD     R4  Daily short-wave radiation (J.m-2.d)                  I
*
* TMDA    R4  24 hour average temperature (degrees C)               I
*
* WN      R4  Average wind speed (m.s-1)                            I
*
* VP      R4  Early morning vapour pressure (kPa)                   I
*
* ETD     R4  Potential evapotranspiration (mm.d-1)                 O
*
* ETRD    R4  Radiation driven part of potential
*
*             evapotranspiration (mm.d-1)                           O
*
* ETAE    R4  Dryness driven part of potential evapotranspiration
*
*             (mm.d-1)                                              O
*
* DT      R4  Estimated temperature difference between surface
*
*             height and reference height (degrees C)               O
*
*
*
* Fatal error checks : TMDI < 0
*
*                      ISURF < 1 and > 3
*
*                      combination of ANGA and ANGB value, see IF
line *
* Warnings           : RDD < 0.5E6
*
*                      WN < 0.2
*
*                      VP > 1.4*saturated
*
* Subprograms called : SASTRO, SVPS1
*
* Required libraries : TTUTIL
*
* File usage         : none
*
*-------------------------------------------------------*
      SUBROUTINE SETPMD (IUNITO, OUTPUT,IDOY, LAT , ISURF, RF, ANGA,
     &                   ANGB, TMDI,
     &                   RDD , TMDA, WN   , VP,
```

```
     &                     ETD , ETRD, ETAE ,  DT)
      IMPLICIT NONE

*     Formal declarations
      INTEGER IDOY, ISURF , IUNITO
      REAL LAT,RF,ANGA,ANGB,TMDI,RDD,TMDA,WN,VP,ETD,ETRD,ETAE,DT
      LOGICAL OUTPUT

*     Local declarations
      INTEGER INLOOP,ILW
      REAL LHVAP,PSCH,SIGMA,RHOCP,RBGL,VPS,VPSL,HUM,VPD,ANGOT, DAYL
      REAL DATMTR,LIMIT,RDLOI,RDLII,RDLO,RDLI,RDN,CLEAR,FU2
      REAL EA,RE,DTN,VPS2
      REAL DUMR1,DUMR2,DUMR3,DUMR4,DUMR5,DUMR6,DUMR7
      REAL RCAN, RLEAF, RAE
      LOGICAL EQUIL

*     Parameters
      PARAMETER (LHVAP = 2454.E3, PSCH = 0.067, SIGMA = 5.668E-8)
      PARAMETER (RHOCP = 1200.   , RBGL = 8.31436)
      PARAMETER (RLEAF = 150., RAE = 45.)
      SAVE

*     Checks

      IF (TMDI.LT.0.) CALL FATALERR
     &   ('SETPMD','Undefined iteration')
      IF (RDD.LT.0.5E6) WRITE (*,'(1X,A,G12.5,A)')
     &   'WARNING from SETPMD: Low short-wave radiation =',RDD,'
J/m2/d'
      IF (WN.LT.0.2) WRITE (*,'(1X,A,G12.5,A)')
     &   'WARNING from SETPMD: Low wind speed =',WN,' m/s'

*     decide which calculation for longwave radiation must be used
      IF (ANGA.EQ.0..AND.ANGB.EQ.0.) THEN
*        use Swinbank formula
         ILW = 1
      ELSE IF (ANGA.GT.0..AND.
     &         ANGB.GT.0..AND.
     &        (ANGA+ANGB).GT.0.5.AND.
     &        (ANGA+ANGB).LT.0.9) THEN
*        use Brunt formula
         ILW = 2
      ELSE
         CALL FATALERR ('SETPMD','illegal longwave radiation option')
*         CALL ERROR ('SETPMD','illegal longwave radiation option')
      END IF

      CALL SVPS1 (TMDA, VPS, VPSL)
      HUM = VP/VPS

      IF (HUM.GT.1.) THEN
         VPD = 0.
         IF (HUM.GT.1.4) WRITE (*,'(2A)') ' WARNING from SETPMD:',
     &      ' Vapour pressure more than 40% greater than saturated !'
      ELSE
         VPD = VPS-VP
      END IF

*     Longwave radiation (J/m2/s and J/m2/d) and net radiation

      CALL SASTRO (IDOY,LAT,
     &             DUMR1,ANGOT,DAYL,DUMR3,DUMR4,DUMR5,DUMR6,DUMR7)
      DATMTR = LIMIT (0.,1.,RDD/ANGOT)

      RDLOI  = SIGMA*(TMDA+273.16)**4
      RDLO   = 86400.*RDLOI
      IF (ILW.EQ.1) THEN
*        Swinbank formula for net longwave radiation
         RDLII  = DATMTR*(5.31E-13*(TMDA+273.16)**6-RDLOI)/0.7+RDLOI
         RDLI   = 86400.*RDLII
      ELSE IF (ILW.EQ.2) THEN
*        Brunt formula for net longwave radiation
         CLEAR = LIMIT (0., 1., (DATMTR-ANGA)/ANGB)
         RDLII = SIGMA*(TMDA+273.16)**4*(1.-(0.53-0.212*SQRT(VP))*
     &           (0.2+0.8*CLEAR))
         RDLI   = 86400.*RDLII
      END IF

      RDN = (1.-RF)*RDD+RDLI-RDLO
      RCAN = RLEAF/3

      ETRD = (VPSL*RDN)/(LHVAP*(VPSL + PSCH*(1.+RCAN/RAE)))
      ETAE = (DAYL/24.)* ((RHOCP*VPD)/(RAE/86400.))/
     &                    (LHVAP*(VPSL + PSCH*(1.+RCAN/RAE)))
      ETD   = ETRD+ETAE

       IF (OUTPUT) THEN
*         States
          CALL OUTDAT (2, 0, 'ETRD'   , ETRD)
          CALL OUTDAT (2, 0, 'ETAE'   , ETAE)
          CALL OUTDAT (2, 0, 'RDN'    , RDN)
          CALL OUTDAT (2, 0, 'VPSL'   , VPSL)
          CALL OUTDAT (2, 0, 'LHVAP'  , LHVAP)
          CALL OUTDAT (2, 0, 'PSCH'  ,  PSCH)
          CALL OUTDAT (2, 0, 'RCAN'   , RCAN)
          CALL OUTDAT (2, 0, 'RAE'  ,   RAE)
          CALL OUTDAT (2, 0, 'RDD'   , RDD)
          CALL OUTDAT (2, 0, 'RDLI'  , RDLI)
          CALL OUTDAT (2, 0, 'RDLO'  , RDLO)
          CALL OUTDAT (2, 0, 'RF'  , RF)
       END IF
      RETURN
     END
```

Subroutine model2

```
PROGRAM MAIN
      CALL FSE
      END

*-----------------------------------------------------*
* SUBROUTINE MODEL2
*
* Authors: Daniel van Kraalingen
*          Wouter Gerritsma
*          Liesje Mommer
* Date   : 5-Jul-1993, Version: 1.1
*
* Update   11 May 1998
* Purpose: This subroutine is the interface routine between the FSE-
*
*          driver and the simulation models. This routine is called
*
*          by the FSE-driver at each new task at each time step. It
*
*          can be used by the user to specify calls to the different
*
*          models that have to be simulated
*
*
*
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)
*
* name   type meaning                                    units
class *
* ----   ---- -------                                    -----  ----
- *
* ITASK   I4  Task that subroutine should perform           -      I
*
* IUNITD  I4  Unit that can be used for input files         -      I
*
* IUNITO  I4  Unit used for output file                     -      I
*
* IUNITL  I4  Unit used for log  file                       -      I
*
* FILEI1  C*  Name of input file no. 1                      -      I
*
* FILEI2  C*  Name of input file no. 2                      -      I
*
* FILEI3  C*  Name of input file no. 3                      -      I
*
* FILEI4  C*  Name of input file no. 4                      -      I
*
* FILEI5  C*  Name of input file no. 5                      -      I
*
* OUTPUT  L4  Flag to indicate if output should be done      -      I
*
* TERMNL  L4  Flag to indicate if simulation is to stop      -
I/O *
* DOY     R4  Day number within year of simulation (REAL)    d      I
*
* IDOY    I4  Day number within year of simulation (INTEGER) d      I
*
* YEAR    R4  Year of simulation (REAL)                      y      I
*
* IYEAR   I4  Year of simulation (INTEGER)                   y      I
*
* TIME    R4  Time of simulation                             d      I
*
* STTIME  R4  Start time of simulation                       d      I
*
* FINTIM  R4  Finish time of simulation                      d      I
*
* DELT    R4  Time step of integration                       d      I
*
* LAT     R4  Latitude of site                          dec.degr.   I
*
* LAT     R4  Latitude of site (dec.degr.)                          I
*
* LONG    R4  Longitude of site (dec.degrees)                       I
*
* ELEV    R4  Elevation of site (m)                                 I
*
* WSTAT   C6  Status code from weather system                -      I
*
* WTRTER  L4  Flag whether weather can be used by model      -      O
*
* RDD     R4  Daily shortwave radiation                   J/m2/d    I
*
* TMMN    R4  Daily minimum temperature                  degrees C  I
*
* TMMX    R4  Daily maximum temperature                  degrees C  I
*
* VP      R4  Early morning vapour pressure                 kPa     I
*
* WN      R4  Average wind speed                            m/s     I
*
* RAIN    R4  Daily amount of rainfall                      mm/d    I
*
*
*
* Fatal error checks: none
*
* Warnings          : none
*
* Subprograms called: models as specified by the user
*
```

```
* File usage        : none
*
*-----------------------------------------------------------------
      SUBROUTINE MODELS (ITASK , IUNITD, IUNITO, IUNITL,
     &                   FILEIT, FILEI1, FILEI2, FILEI3, FILEI4,
     &                   FILEI5,
     &                   OUTPUT, TERMNL,
     &                   DOY    , IDOY   , YEAR   , IYEAR,
     &                   TIME   , STTIME, FINTIM, DELT ,
     &                   ANGA   , ANGB   , FRPAR  ,
     &                   LAT    , LONG   , ELEV   , WSTAT , WTRTER,
     &                   RDD    , TMMN   , TMMX   , VP    , WN, RAIN)
      IMPLICIT REAL (A-Z)
*      IMPLICIT NONE

*     Formal parameters
      INTEGER   ITASK, IUNITD, IUNITO, IUNITL, IDOY, IYEAR
      REAL DOY, YEAR, TIME, STTIME, FINTIM, DELT, LAT
      REAL RDD, TMMN, TMMX, VP, WN, RAIN
      CHARACTER FILEIT*(*), FILEI1*(*), FILEI2*(*)
      CHARACTER FILEI3*(*), FILEI4*(*), FILEI5*(*)
      LOGICAL   OUTPUT, TERMNL, WTRTER
      CHARACTER WSTAT*6
*      CHARACTER*9 CLFILE

*     Local variables
*      INTEGER IWVAR
      CHARACTER WUSED*6
      CHARACTER*80 WATMOD, ETMOD, PLTMOD

*     Water balance declarations
      INTEGER NLXM, NL
      PARAMETER (NLXM=10)
      REAL TRWL(NLXM) , TKL(NLXM) , WCAD(NLXM)    , WCWP(NLXM)
      REAL WCFC(NLXM) , WCST(NLXM), FLXQT(NLXM+1), WCLQT(NLXM)
      REAL FLXCU(NLXM+1), ZRTMS
      LOGICAL GIVEN

      SAVE

*     code for the use of RDD, TMMN, TMMX, VP, WN, RAIN (in that
order)
*     a letter 'U' indicates that the variable is Used in
calculations
      DATA WUSED /'------'/

      DATA GIVEN /.FALSE./
      IF (ITASK.EQ.1) THEN

*        ----------------------
*        Initialization section
*        ----------------------

         CALL RDINIT (IUNITD, IUNITL, FILEIT)

*        Read modules to be used
         CALL RDSCHA ('PLTMOD', PLTMOD)
         CALL UPPERC (PLTMOD)
         CALL RDSCHA ('WATMOD', WATMOD)
         CALL UPPERC (WATMOD)
         CALL RDSCHA ('ETMOD' , ETMOD)
         CALL UPPERC (ETMOD)

*         CALL RDSCHA ('CLFILE' , CLFILE)
*         CALL UPPERC (CLFILE)

         CLOSE (IUNITD)

*        Write line to mark start of new run
         WRITE (IUNITO,'(A,76A1)') '*',('=',I1=1,76)

*        Log messages to output file
         WRITE (IUNITO,'(A)') '*'
         WRITE (IUNITO,'(A)') '* FSE driver info:'
         WRITE (IUNITO,'(A,T7,A,I5,A,I4,A)')
     &     '*','Year:',IYEAR,', day:',IDOY,', System start'

         WRITE (IUNITO,'(A)') '*'
         WRITE (IUNITO,'(A)') '* Modules used:'

*        Choose and check evapotranspiration modules
         IF (ETMOD.EQ.'PENMAN') THEN
            WRITE (IUNITO,'(A,T7,A)')
     &        '*','SETPMD: Penman evapotranspiration'
            WUSED(1:5) = 'UUUUU'
         ELSE IF (ETMOD.EQ.'MAKKINK') THEN
            WRITE (IUNITO,'(A,T7,A)')
     &        '*','SETMKD: Makkink evapotranspiration'
            WUSED(1:3) = 'UUU'
         ELSE IF (ETMOD.EQ.'PRIESTLEY TAYLOR') THEN
            WRITE (IUNITO,'(A,T7,A)')
     &        '*','SETPTD: Priestley Taylor evapotranspiration'
            WUSED(1:3) = 'UUU'
         ELSE
            CALL FATALERR
     &       ('MODELS','unknown module name for evapotranspiration')
         END IF

*        Choose and check water balance modules
         IF (WATMOD.EQ.'POTENTIAL') THEN
            WRITE (IUNITO,'(A,T7,A)')
     &        '*','DRPOT : Water balance for potential situations'
         ELSE IF (WATMOD.EQ.'SAHEL') THEN
            WRITE (IUNITO,'(A,T7,A)')
```

```
     &       '*','DRSAHE: Tipping bucket water balance version 1.4'
           WUSED(6:6) = 'U'
        ELSE
           CALL FATALERR
     &     ('MODELS','unknown module name for water balance')
        END IF

*       Choose and check crop modules
        IF (PLTMOD.EQ.'CACAO'.AND.
     &      WATMOD.EQ.'POTENTIAL') THEN
           WRITE (IUNITO,'(A,T7,A,/,A,T7,A)')
     &       '*','CASE2:  Cacao at potential production,',
     &       '*','          Version February 1997'
           WUSED(1:3) = 'UUU'

        ELSE IF (PLTMOD.EQ.'CACAO'.AND.
     &           WATMOD.EQ.'SAHEL') THEN
           WRITE (IUNITO,'(A,T7,A,/,A,T7,A)')
     &       '*','CASE2: Cacao at water limited production,',
     &       '*','         Version February 1997'
           WUSED(1:3) = 'UUU'

        ELSE IF (PLTMOD.EQ.'NO CROP') THEN
           WRITE (IUNITO,'(A,T7,A)')
     &       '*','NO CROP: no crop'

        ELSE
           CALL FATALERR
     &     ('MODELS','unknown module name for plant')
        END IF

*       Mention of the use of the weatherfile
*        WRITE (IUNITO,  FILE = CLFILE, STATUS =OLD)

*       Avoid FORCHECK errors
        WCLQT(1)  = -99.
        WCST(1)   = -99.
        TAI       = -99.
     END IF

*    Check weather data availability
     IF (ITASK.EQ.1.OR.ITASK.EQ.2.OR.ITASK.EQ.4) THEN

        IF (WSTAT(6:6).EQ.'4') THEN
           RAIN       = 0.
           WSTAT(6:6) = '1'
           IF (.NOT.GIVEN) THEN
*               WRITE (*,'(2A)') ' Rain not available,',
*    &            ' value set to zero, (patch DvK, Jan 1995)'
              WRITE (IUNITL,'(2A)') ' Rain not available,',
     &          ' value set to zero, (patch DvK, Jan 1995)'
              GIVEN = .TRUE.
           END IF
        END IF

        DO I1=1,6
*          Is there an error in the I1-th weather variable ?
           IF (WUSED(I1:I1).EQ.'U' .AND.
     &         WSTAT(I1:I1).EQ.'4') THEN
              WTRTER = .TRUE.
              TERMNL = .TRUE.
              RETURN
           END IF
        END DO
     END IF

*    Calculate average temperature
     TMDA = (TMMX+TMMN)/2.

     IF (ITASK.EQ.2) THEN

*       ------------------------
*       Rate calculation section
*       ------------------------

*       Reflection of soil
        RFS = 0.25*(1.-0.5*WCLQT(1)/WCST(1))

*       Total reflection
*       RF  = RFS*EXP(-0.5*GAI)+0.25*(1.-EXP(-0.5*GAI))
        RF  = RFS*EXP(-0.5*TAI)+0.25*(1.-EXP(-0.5*TAI))

        IF (ETMOD.EQ.'PENMAN') THEN

*         Penman evapotranspiration
*         ISURF 3, Short grass cover
*         ISURF 4, Tree crops
          CALL SETPMD (IUNITO, OUTPUT, IDOY,LAT,3,RF,ANGA,ANGB,TMDI,
     &                 RDD, TMDA, WN,VP,
     &                 ETD, ETRD,ETAE,  DT)

*          Calculate potential soil evaporation taking into account
*          the standing crop
           EVSC = EXP (-0.5*TAI)*(ETRD+ETAE)

        ELSE IF (ETMOD.EQ.'MAKKINK') THEN

*          Makkink evapotranspiration
*           CALL SETMKD (RDD, TMDA, ETD)

*         Estimate radiation driven and wind and humidity driven
*         part

           ETRD = 0.75*ETD
```

```
            ETAE = ETD-ETRD

*           Calculate potential soil evaporation taking into account
*           the standing crop
            EVSC = EXP (-0.5*TAI)*ETD

         ELSE IF (ETMOD.EQ.'PRIESTLEY TAYLOR') THEN

*           Priestley Taylor evapotranspiration
            CALL SETPTD (IDOY,LAT,RF,RDD,TMDA,ETD)

*           Estimate radiation driven and wind and humidity driven
*           part
            ETRD = 0.75*ETD
            ETAE = ETD-ETRD

*           Calculate potential soil evaporation taking into account
*           the standing crop
            EVSC = EXP (-0.5*TAI)*ETD

         END IF

*        Make sure potential soil evaporation is always positive
*        the amount of dew is unreliable anyhow
         EVSC = MAX (EVSC, 0.)

      END IF ! end ITASK=2

       CALL INTERCEPT (ITASK, IUNITD, IUNITL, FILEI1,
     &                                  RAIN, RAINS, PINT)


*     Choose water balance module
      IF (WATMOD.EQ.'SAHEL') THEN
*        call to version 1.4 of DRSAHE
         CALL DRSAHE (ITASK , IUNITD, IUNITO, FILEI2,
     &                IDOY  , IYEAR , DELT  , OUTPUT,
     &                NLXM  , NL    , EVSC  , RAINS , TRWL,
     &                TKL   , ZRTMS ,
     &                WCAD  , WCWP  , WCFC  , WCST  ,
     &                EVSW  , FLXQT , WCLQT ,
     &                DRAICU, EVSWCU, RAINCU, TRWCU , FLXCU)
*    &                WCADX , WCWPX , WCFCX , WCSTX,

*        Adapted call for version 1.8
*         CALL DRSAHE (ITASK , IUNITD, IUNITL, FILEI2, NLXM,
*    &                 IDOY  , IYEAR , DELT  , OUTPUT,
*    &                 EVSC  , RAIN2 , TRWL  ,
*    &                 ZRTMS , NL    , TKLX  ,
*    &                 WCAD  , WCWP  , WCFC  , WCST  ,
*    &                 EVSW  , FLXQT , WCLQT ,
*    &                 DRAICU, EVSWCU, RAINCU, TRWCU , FLXCU)

      ELSE IF (WATMOD.EQ.'POTENTIAL') THEN

*        Daan's original call
*        CALL DRPOT (ITASK , NLXM  , NL    , EVSC ,
*    &               TKL   , ZRTMS , WCAD  , WCWP , WCFC, WCST,
*    &               EVSW  , FLXQT , WCLQT ,
*    &               DRAICU, EVSWCU, RAINCU, TRWCU, FLXCU)

*       kees call
        CALL DRPOT (ITASK, NLXM , NL,
     &              TKL  , ZRTMS, WCAD , WCWP , WCFC , WCST,
     &              WCLQT)

      END IF

*     Choose crop module
      IF (PLTMOD.EQ.'CACAO') THEN

      CALL CASE2 (PLTMOD, ITASK , IUNITD, IUNITO, IUNITL, FILEI1,
     &            OUTPUT, TERMNL,
     &            DOY   , IDOY  , IYEAR , DELT  , TIME  , STTIME,
     &            LAT   , FRPAR , RDD   , TMMN  , TMMX  ,
     &            NLXM  , NL    , TRWL  , TKL   , ZRTMS ,
     &            WCLQT , WCWP  , WCFC  , WCST  ,
     &            EVSC  , ETRD  , ETAE  , PINT  ,
     &            GAI   , TAI   ,RAIN )

      ELSE IF (PLTMOD.EQ.'NO CROP') THEN

*        CALL NOCROP (NLXM, TRWL, RAIN, RAIN2, GAI, TAI, LAI,
*    &                WLV , WST , WSO , DVS)

         CALL NOCROP (NLXM, TRWL, RAIN, RAINS, GAI, TAI)
      END IF

       IF ((OUTPUT).AND.(ITASK.EQ.2)) THEN
          CALL OUTDAT (2, 0, 'DOY'   , DOY  )
          CALL OUTDAT (2, 0, 'YEAR'  , YEAR )
          CALL OUTDAT (2, 0, 'ETD'   , ETD  )
          CALL OUTDAT (2, 0, 'ETRD'  , ETRD )
          CALL OUTDAT (2, 0, 'ETAE'  , ETAE )
          CALL OUTDAT (2, 0, 'EVSC'  , EVSC )
          CALL OUTDAT (2, 0, 'RAIN'  , RAIN )
          CALL OUTDAT (2, 0, 'RAINS'  , RAINS )

      END IF


      IF (ITASK.EQ.4) THEN
         WRITE (IUNITO,'(A)') '*'
         WRITE (IUNITO,'(A)') '* FSE driver info:'
```

```
        WRITE (IUNITO,'(A,T7,A,I5,A,I4,A)')                              END
     &      '*','Year:',IYEAR,', day:',IDOY,', System end'
      END IF

      RETURN
      END

      SUBROUTINE INTERCEPT (ITASK, IUNITD, IUNITL, FILEP,
     &                               RAIN, RAINS, PINT)

      IMPLICIT NONE

*     Formal parameters
      INTEGER ITASK, IUNITD, IUNITL
      REAL RAIN, RAINS, PINT
      CHARACTER FILEP*(*)

*     Local declarations
      REAL TFALL, STEMFL
      REAL TFALA, TFALB, STFLA, STFLB
      REAL LIMIT

      IF (ITASK.EQ.1) THEN

*     Initialize input file
      CALL RDINIT (IUNITD, IUNITL, FILEP)

*     Stemflow and troughfall parameters
      CALL RDSREA ('TFALA'   , TFALA  )
      CALL RDSREA ('TFALB'   , TFALB  )
      CALL RDSREA ('STFLA'   , STFLA  )
      CALL RDSREA ('STFLB'   , STFLB  )

      CLOSE (IUNITD)

      ELSE IF (ITASK.EQ.2) THEN

*       Troughfall (TFALL), Stemflow (STFLOW) and
*       Rainfall interception (PINT)
        TFALL    = LIMIT (0., RAIN, TFALA*RAIN + TFALB)
! [mm d-1]
        STEMFL   = LIMIT (0., RAIN, STFLA*RAIN + STFLB)
! [mm d-1]
        PINT     = MAX(0.,RAIN - TFALL - STEMFL)
! [mm d-1]

*       Rainfall reaching the soil (RAINS)(= TFALL + STEMFL)
        RAINS    = RAIN-PINT
! [mm d-1]

      END IF
      RETURN
```

Appendix1a

Plant datafile case2.dat

```
*-----------------------------------------------------------*
*
*
* Plant data file to be used with CAcao Simultion Engine
*
*
*
*-----------------------------------------------------------*


* Initial conditions

* Planting density
   NPL     = 920.              ! [trees ha-1] (Thong & Ng, 1978) GHANA
SET
*    NPL    = 1347.              ! 1980 practise at BAL ,MALAYSIA SET

* Age at the start of simulation and weight of single tree biomass
components
*  AGEI    = 0.             ! [days after field planting] (12 months)
*  WRTI    = 0.148            ! [kg DM tree-1] (Thong & Ng, 1978; 12
months)
*  WWDI    = 0.35             ! [kg DM tree-1] (Thong & Ng, 1978; 12
months)
*  WLVI    = 0.18             ! [kg DM tree-1] (Thong & Ng, 1978; 12
months)
*  WPDI    = 0.00             ! [kg DM tree-1] (Thong & Ng, 1978; 12
months)

* Age at the start of simulation and weight of single tree biomass
components
*  AGEI    = 850.             ! [days after field planting] (28
months)
*  WRTI    = 2.19             ! [kg DM tree-1] (Thong & Ng, 1978; 28
months)
*  WWDI    = 5.46             ! [kg DM tree-1] (Thong & Ng, 1978; 28
months)
*  WLVI    = 3.92             ! [kg DM tree-1] (Thong & Ng, 1978; 28
months)
*  WPDI    = 0.35             ! [kg DM tree-1] (Thong & Ng, 1978; 28
months)

* Age at the start of simulation and weight of single tree biomass
components
*  AGEI    = 1190.            ! [days after field planting] (39
months)
*  WRTI    = 4.38             ! [kg DM tree-1] (Thong & Ng, 1978; 39
months)
*  WWDI    = 8.96             ! [kg DM tree-1] (Thong & Ng, 1978; 39
months)
*  WLVI    = 5.70             ! [kg DM tree-1] (Thong & Ng, 1978; 39
months)
*  WPDI    = 2.37             ! [kg DM tree-1] (Thong & Ng, 1978; 39
months)

* Age at the start of simulation and weight of single tree biomass
components
 AGEI    = 1525.            ! [days after field planting] (51 months)
*  WRTI    =  6.04            ! [kg DM tree-1] (Thong & Ng, 1978; 51
months)
  WWDI    = 15.06            ! [kg DM tree-1] (Thong & Ng, 1978; 51
months)
  WLVI    =  7.64            ! [kg DM tree-1] (Thong & Ng, 1978; 51
months)
  WPDI    =  2.37            ! [kg DM tree-1] (Thong & Ng, 1978; 51
months)
*  WPDI = 3.09

* Age at the start of simulation and weight of single tree biomass
components
*  AGEI    = 1860.            ! [days after field planting] (61
months)
*  WRTI    =  7.58            ! [kg DM tree-1] (Thong & Ng, 1978; 61
months)
*  WWDI    = 26.58            ! [kg DM tree-1] (Thong & Ng, 1978; 61
months)
*  WLVI    =  9.56            ! [kg DM tree-1] (Thong & Ng, 1978; 61
months)
*  WPDI    =  1.18            ! [kg DM tree-1] (Thong & Ng, 1978; 61
months)


* Root growth parameters
* Length tap root (x=age(d), y=length(m))(Himme, 1959)
  LTRTB = 0.,0.37,  5110.,1.3,  9125.,1.5,  36500.,1.5

* Diameter tap root (x=age (d), y diameter (m)) (Himme, 1959)
* DTRTB = 0.,0., 100.,0.03,  5110.,0.12,  9125.,0.21,  36500., 1.5

PGLA=0.0008
PGLB=0.001

* Maximum fine roots in the soil(y)(kg ha-1) depends on age (x).
*(After Kummerow, 1981)
  WMAXTB = 0.,200., 2190.,2830., 5470.,13910., 36500.,13910.

*The tables GLTRTB and GDTRTB give the potential growth rate
*(m d-1) of the length and diameter of the taproot,
*related to their length and diameter(m).
 GLTRTB = 0.,0.0001, 1.5,0.0001,  2.,0., 10.,0.
 GDTRTB = 0.,0.00002, 1.5, 0.00002, 2.,0., 10.,0.
```

```
* Fraction roots of fine roots able to take up water (Kummerow, 1981)
  FFRT = 0.2

* Mean diameter (m) and specific root length (m kg-1) of the two root
* classes able to take up water (Kummerow, 1981)
  DIAM1 = 0.00022
  DIAM2 = 0.0015
  SPRTL1 = 36000.
  SPRTL2 = 3000.

*specific weight of wood (kg m-3)(Value of Boyer (1973), added 10%
because of compaction)
  SW = 390.

* Setpoint root:shoot ratio
 RSSET = 0.2

*Reserve fact
* RESF = 1.00
RESF = 1.25     !Ghana

*Time coefficient, delay time
 TAU = 10.
 TAU2 = 1.                                          !d

* Sink strength for pod growth, based on End et al. (1991)
  SSTB  =    0.0,0.0, 0.300,.05, 0.467,0.17, 0.533,0.41, 0.633,.94,
           0.667,1.0, 0.778,.94, 0.867,0.17,   1.0,0.0,   1.1,0.0

* Photosynthesis parameters
*  AMX    = 7.0      ! Very vigorous, Hutcheon (1977)
  AMX    = 13.3    !  Highest observed by Yapp & Hadley (1991)
  EFF    = 0.45    !  12.5 microgram CO2/J  = 0.45 kg
(CO2/ha/h)/(J/m2/s)
  AMTMPT = 0.,0., 30.,1., 33.,1., 40.,0.          ! influence of
temperature

* Light absorption parameters
  KDFL    = 0.60
  KDFT    = 0.50

* Maintenance respiration parameters
  Q10     = 2.                    ! q10
  TREF    = 25.                   ! reference temperature
  FRSUPW = 0.4                   ! Fraction supporting (dead) wood

  MAINLV = 0.0069                 ! maintenance coefficient leaves
  MAINWD = 0.0024                 ! maintenance coefficient wood
  MAINRT = 0.0047                 ! maintenance coefficient roots
  MAINFRT = 0.0047
  MAINTRT = 0.0024
  MAINPD = 0.016                  ! maintenance coefficient pods

* Growth respiration parameters
  ASRQRT = 1.49415
  ASRQFRT = 1.49415
  ASRQTRT = 1.56871
  ASRQWD = 1.56871
  ASRQLV = 1.65600
  ASRQPD = 1.75554

* Carbon content plant components
  CFFRT=0.50080
  CFTRT=0.51996
  CFWD=0.51996
  CFLV=0.46737
  CFPD=0.50895

* Weight ratio of beans per pod
  BEAPOD = 0.55                 !g bean g-1 pod

* partitioning parameters
  FSHTB  = 0.00,0.8, 20000.,0.8
  FLVTB  = 0.00,0.55, 548.,0.55, 1000.,0.41, 2000.,0.38, 20000.,0.38
  FWDTB  = 0.00,0.45, 548.,0.45, 1000.,0.44, 2000.,0.40, 20000.,0.40
  FPDTB  = 0.00,0.00, 548.,0.00, 1000.,0.15, 2000.,0.22, 20000.,0.22

*  FLVTB  = 0.00,0.55, 365.,0.55, 1000.,0.40, 2000.,0.40, 20000.,0.40
*  FWDTB  = 0.00,0.45, 365.,0.45, 1000.,0.35, 2000.,0.35, 20000.,0.35
*  FPDTB  = 0.00,0.00, 365.,0.00, 1000.,0.25, 2000.,0.25, 20000.,0.25

* Partitioning TapRooT and Partitioning Fine Roots
PTRT = 0.2
PFRT = 0.8

* Leaf area growth parameters

* Geurs (1971) (age,[ha leaf /kg leaf])
* FSLATB  = 0.,0.001456, 10000.,0.001456

* Function based on Thong & Ng (1978)
  FSLATB  = 0.,.000982, 480.,.000982, 1140.,.001229, 1800.,.001385,
        20000.,.001385

! Estimated maximum leaf age [days]
*   MAXLAG = 250.           !SET FOR mALAYSIA
*   MINLAG =  90.           ! Estimated minimum leaf age [days]
   MAXLAG = 365.            !SET FOR GHANA
   MINLAG =  60.

  MINCON = 0.07
  FDRWD  = 0.5
```

Appendix1a

```
  FDRRT   = 0.8

* Canopy height distribution
  HGHT = 3.50
  HGHL = 0.75

* Characteristics shade trees
*  TSLAIL = 0.0,4., 1000.,2., 1500.,0.3, 20000.,.3       ! Coconuts
*  TSLAIT = 0.0,0.02, 20000.,0.02
   TSLAIL = 0.0,0., 1000.,0., 1500.,0., 20000.,0.
   TSLAIT = 0.0,0., 20000.,0.

  SKDFL = 0.44                ! Extinction coefficient Shade Leaves
  SKDFT = 0.5                 ! Extinction coefficient Shade
Trunk/Branches
  SHGHL =  4.0                ! Height of shade tree crowns
  SHGHT = 10.                 ! Total height of shade tree
  SAMX  = 30.                 ! Maximum rate of photosynthesis shade
trees
  SEFF  =  0.45               ! Light use efficiency shade trees

* Water relation declarations
* ============================
* Troughfall and Stemflow

* Based on Opakunle (1989)
*  TFALA = 0.719; TFALB = 2.0980
*  STFLA = 0.018; STFLB = 0.0502

* Based on Boyer (1970)
  TFALA = 0.927;   TFALB = -0.789
  STFLA = 0.0  ;   STFLB = 0.0

* EDPTFT = 0.,0.15, 0.15,0.6, 0.3,0.8, 0.5,1., 1.,1.
* ZRTI   = 1.00             ! Initial rooting depth [m]
* EZRTC  = 0.001             ! Constant of root elongation  [m/d]
* ZRTMC  = 2.00             ! Maximum rooting depth as crop
characteristic
TRANSC = 1.5              ! mm day-1
WCWET  = 0.40             ! [cm3 cm-3]
```

Appendix1a

Soil datafile Soilciv1.dat

```
* This soil description file approximates physical soil conditions
*NLXM = 10
*NL    = 4                        ! Number of layers
*TKL   = 0.10, 0.30, 0.30, 1.50  ! Thickness of layers (m)

NL = 6
TKL = 0.10, 0.20, 0.30, 0.30, 0.30, 0.30

SWIT8 = 1                        ! (1) Driessen equation
                                 ! (2) van Genuchten equation
                                 ! (3) Linear interpolation
                                 ! (4) User defined
SWIT9 = 2                        ! Use predefined texture classes

* Provide texture classes for Driessen soil (SWIT9 = 2)
TYL   = 12., 9., 8., 8., 8., 8.

*WCST = 0.58, 0.53, 0.58, 0.55, !Saturated water content  pF 0
*       0.58, 0.57, 0.70
*WCFC = 0.40, 0.35, 0.39, 0.25, !Watercontent at field capacity pF 2
*       0.48, 0.37, 0.60
*WCWP = 0.23, 0.15, 0.22, 0.12, !Watercontent at wilting point pF 4.2
*       0.19, 0.18, 0.20
*WCAD = 7*0.025                 !Watercontent air dry pF 7.0

* initialization

SWIT6 = 1             ! (1) Initial water content field capacity
                      ! (2) Initial water content user defined
                      ! (3) Initial water content wilting point
* Provide Array with initial water contents when SWIT6 = 2
* WCLQTM = 0.40, 0.35, 0.39, 0.25, ! Initial water content
*(Field capacity)
*         0.48, 0.37, 0.60

EES = 20.  !m-1                  ! Evaporation proportionality factor
RO1 = 10.0 !mm                    ! Intercepted rain
RO2 = 0.15 !-                     ! Proportionality factor
```

Appendix1a

Timer file timer.dat

```
*-----------------------------------------------------------*
*
*
* Timer data file to be used by FSE 2.0
*
*
*
*-----------------------------------------------------------*

*
* Weather data specification
*

WTRDIR = 'c:\fse\meteo\climd\ ' ! Directory of weather data
CLFILE = 'ghataf.wof'
IFLAG  = 1101             ! Indicates where weather error and
warnings
                          ! go (1101 means errors and warnings to
log
                          ! file, errors to screen, see FSE manual)
IWEATH = 1                ! Flag indicating the weather system used
                          ! 0,1 Wofost
                          ! 2 Cabo daily weather
IRNDAT = 1                ! Flag indicating rainfall system when
                          ! IWEATH = 0, 1
                          ! 0 Generated
                          ! 1 Distributed
                          ! 2 Observed
*
* Modules specification
*
PLTMOD = 'CACAO'
* PLTMOD = 'NO CROP'

* WATMOD = 'POTENTIAL'
WATMOD = 'SAHEL'
* WATMOD = 'SAWAH'

ETMOD = 'PENMAN'
* ETMOD = 'MAKKINK'
* ETMOD = 'PRIESTLEY/TAYLOR'

* Site specific parameters for Angstrom formula
*  ANGA = 0.29   ; ANGB = 0.39              ! Bah Lias (North
Sumatra, Indonesia)
*  ANGA = 0.27   ; ANGB = 0.54              ! Dami     (West New
Britain, Papua New Guinea)
*  ANGA = 0.29   ; ANGB = 0.42              ! humid tropical zones
(Frere and Popov)
*  ANGA = 0.34   ; ANGB = 0.49              ! Malaysia (Chuah &
Lee)
  ANGA = 0.22   ; ANGB = 0.37               ! Ghana,  Tafo
(Gerritsma)
* Radiation parameter
  FRPAR = 0.5

* Time control variables
*
IYEAR  = 1983              ! Start year of simulation
STTIME = 120.              ! Start day of simulation
FINTIM = 4018.            ! Finish time of simulation
*FINTIM = 294.
DELT   = 1.                ! Time step of integration

*
* Output variables
*

PRDEL  = 10.     ! Time between consecutive outputs to file,
                           ! (when PRDEL=0, no output is generated,
                           ! when PRDEL is very large (i.e. 10000.)
                           ! only initial and terminal output is
                           ! generated
IPFORM = 5                 ! Format of output file:
                           !    0 = no output table,
                           !    4 = normal table,
                           !    5 = tab-delimited (Excel),
                           !    6 = TTPLOT format
COPINF = 'N'               ! Switch variable what should be done with
                           ! the inputfiles:
                           !   'N' = do not copy inputfiles into
                           !         outputfile,
                           !   'Y' = copy inputfiles into outputfile
DELTMP = 'N'               ! Switch variable what should be done with
                           ! the temporary and binary output file:
                           !   'N' = do not delete,
                           !   'Y' = delete
*
* Optional output variables
*

*prsel = 'year', 'doy', 'wrt', 'wtrt', 'wtfrt','WFRT(1)','WFRT(2)',
*       'WFRT(3)', 'WFRT(4)', 'WFRT(5)', 'WFRT(6)', 'ETAE', 'ETRD',
*        'ltrt', 'nla','lai', 'TDRW','AVAIL',
*        'WCLQT(1)', 'TRRM' '<table>'
*PRSEL= 'YEAR','DOY','TDRW','TADRW', 'WRT','pcew',
*        'maint','lai(1)','ltrt', 'wlvg','rsact','<TABLE>'
prsel=  'year', 'doy', 'ptrans', 'atrans','<table>'
*prsel = 'year', 'lai(1)', 'flv', 'fpd' ,'<table>'
                           ! Selection of variables that are printed
in
```

```
                              ! the output table. If PRSEL is inactive
all
                        ! variables are printed, otherwise only those
                              ! that are specified after PRSEL. The
string
                              ! '<TABLE>' means that variables listed to
                              ! the left are put in one table.
*IOBSD  =1983, 365
*         1984, 365
*         1985, 365
*         1986, 365
*         1987, 365
*         1988, 365
*         1989, 365
*         1990, 365
*         1991, 365
*         1992, 365
*         1993, 365

                              ! List of observation data for which
output
                              ! is required. The list should consist of
                              ! pairs of <year>,<day> combinations.
```

Appendix1b

Definition of abbreviations used in CASE2

Name	Description	Units
ACYIEL	Actual yield	kg dry beans ha-1
AGE	Age of tree	d
AGEI	Age at start of simulation	d
AMAX	Actual CO2 assimilation rate at light saturation for individual leaves	kg CO2.ha-1 leaf.h-1
AMTMP	Factor accounting for effect of daytime temperature on AMX	-
AMTMPT	Table of AMTMP as function of daytime temperature	-
AMX	Potential CO2 assimilation rate at light saturation for individual leaves	kg CO2.ha-1 leaf.h-1
ASRQ	Assimilate (CH2O) requirement for 1 kg dry matter production	kg CH2O.kg-1 DM
ASRQFRT	Assimilate (CH2O) requirement for 1 kg fine root dry matter production	kg CH2O kg-1 DM
ASRQLV	Assimilate (CH2O) requirement for 1 kg leaf dry matter production	kg CH2O.kg-1 DM
ASRQPD	Assimilate (CH2O) requirement for 1 kg pod dry matter production	kg CH2O kg-1 DM
ASRQTRT	Assimilate (CH2O) requirement for 1 kg taproot dry matter production	kg CH2O kg-1 DM
ASRQWD	Assimilate (CH2O) requirement for 1 kg wood dry matter production	kg CH2O kg-1 DM
ATRANS	Total actual transpiration rate of the canopy	mm.d-1
AVAIL	Amount of available water in a particular soil compartment	mm
AWURT	Array with rootlet surface area in different soil layers	m2 ha-1
AWURTT	Total rootlet surface area of the roots able to take up water (diameter < 2 mm)	m2 ha-1
BEAPOD	Bean:pod ratio	-
CFFRT	Mass fraction carbon in the fine roots	kg C kg-1 DM
CFLV	Mass fraction carbon in the leaves	kg C.kg-1 DM
CFPD	Mass fraction carbon in the pods	kg C kg-1 DM
CFTRT	Mass fraction carbon in the taproot	kg C kg-1 DM
CFWD	Mass fraction carbon in the wood	kg C kg-1 DM
CHKDIF	Relative difference between carbon added to the crop since initialization and the net carbon flux	-
CHKFL	Net carbon flux into the crop	kg C.ha-1
CHKFRT	Carbon in the fine roots assimilated since simulation started	kg C ha-1
CHKIN	Carbon in the crop accumulated since simulation started	kg C.ha-1
CHKLV	Carbon in the leaves assimilated since simulation started	kg C ha-1
CHKPD	Carbon in the pods assimilated since simulation started	kg C ha-1
CHKRT	Carbon in the roots assimilated since simulation started	kg C ha-1
CHKTRT	Carbon in the taproots assimilated since simulation started	kg C ha-1
CHKWD	Carbon in the wood assimilated since simulation started	kg C ha-1
CO2FRT	CO2 production factor for growth of the fine roots	kg CO2 kg-1 DM
CO2LV	CO2 production factor for growth of leaves	kg CO2.kg-1 DM
CO2PD	CO2 production factor for growth of the pods	kg CO2 kg-1 DM
CO2TRT	CO2 production factor for growth of the taproot	kg CO2 kg-1 DM
CO2WD	CO2 production factor for growth of the wood	kg CO2 kg-1 DM
CROPF	Crop factor for crop water requirement	-
CUMTK2	Cumulative thickness of rooted, soil layers at TIME-DELT	m
CUMTKL	Cumulative thickness of rooted soil layers, intermediate variable	m
DELT	Time interval of integration	d
DEVR	Development rate of pods	d-1
DEVRH	Development rate of pods at high temperature	d-1
DEVRL	Development rate of pods at low temperature	d-1
DFRT	Death rate of fine roots	d-1
DIAM1	Mean diameter of fine roots (diameter < 1 mm)	m
DIAM2	Mean diameter of fine roots (diameter between 1 and 2 mm)	m
DLV	Death rate of leaf biomass	kg leaf.ha-1.d-1
DOY	Day number since 1 January (day of year)	d
DRES	Death rate of the reserves	kg CH2O ha-1 d-1
DTGA	Daily gross total assimilation	kg ha-1 d-1
DTW	Total crop death rate	kg DM ha d-1

DWD	Death rate of wood	kg DM ha-1 d-1
EFF	Initial light use efficiency for individual leaves	kg CO2.ha-1 leaf.h-1.(J.m-2 leaf.s-1)
ETAE	Dryness driven part of potential evapotranspiration	mm.d-1
ETRD	Radiation driven part of potential evapotranspiration	mm.d-1
EVSC	Potential evaporation rate	mm.d-1
FFRT	Fraction finest roots	-
FILEP	File name with which plant parameters are read	-
FLV	Fraction of shoot dry matter allocated to leaves	-
FLVTB	Table of FLV as function of DVS	-
FPD	Fraction of shoot dry matter allocated to pods	-
FPDTB	Table of shoot dry matter allocated to pods	-
FRABS	Fraction absorbed radiation	-
FRPAR	Photosynthetically active fraction of short-wave radiation	-
FRSUPW	Fraction supporting wood	-
FRT	Fraction of total dry matter allocated to roots	-
FRTF	Fine root fraction	-
FSH	Fraction of total dry matter allocated to shoots	-
FSHTB	Table of FSH as function of DVS	-
FSLATB	Function table of SLA	-
FWD	Fraction of shoot dry matter allocated to wood	-
FWDTB	Table of shoot dry matter allocated to wood	-
GAI	Green area index	m2 leaf.m-2 ground
GFRT	Growth rate of fine roots	kg DM ha-1 d-1
GLV	Dry matter growth rate of leaves	kg dm.ha-1 ground.d-1
GMASS	Biomass growth of roots per length, intermediate variable	Kg ha-1 m-1
GPD	Growth rate of pods	kg DM ha-1 d-1
GPHOT	Daily total gross CH2O assimilation of the crop	kg CH2O.ha-1 d.d-1
GPOD	Growth rate of pods	kg DM ha-1 d-1
GRES	Growth rate of reserves	kg CH2O ha-1 d-1
GRT	Dry matter growth rate of roots	kg DM.ha-1.d-1
GTRT	Growth rate of taproot	kg DM ha-1 d-1
GTW	Gross growth rate of crop dry matter, including translocation	kg DM.ha-1.d-1
GWD	Growth rate of wood	kg DM ha-1 d-1
HGHL	Lower height of a species in the canopy	m
HGHT	Total height of a species in the canopy	m
HI	Harvest index	kg storage organs.kg-1 TADRW
I1	DO-loop counter	
IAMTMN	Length of table AMTMPT	-
IDOY	Day number within year of simulation	d
IDOYO	Day number at the previous step of simulation	d
IFLVN	Length of table FLVTB	-
IFPDN	Length of table FPDTB	-
IFSHN	Length of table FSHTB	-
IFSLAN	Length of table FSLATB	-
IFWDN	Length of table FwDTB	-
ILD	Intermediate variable	-
INS	Number of species	-
IPLD	Intermediate variable	-
IPOD	Number of pod classes	-
ISLAIL	Length of table SLAITB	-
ISSN	Length of table SSTB	-
ITABLE	Declared length of many of the interpolation tables	-
ITASK	Task that subroutine should perform	-
IUNITD	Unit number that is used for input files	-
IUNITL	Unit number that is used for log file	-

IYEAR	Year of simulation	y
KDF	Extinction coefficien for leaves	-
KS	Moisture coefficient of the top soil	%-1
LA	Array of leaf area per age class	-
LAI	Green leaf area index	m2 leaf.m-2 ground
LAT	Latitude of site	dec.degr.
LTRT	Length of taproot	m
LTRTB	Table of length of taproot	m
LTRTI	Initial length of taproot	m
LTRTMN	Number of elements of LTRTB	-
LWURT	Total length of roots able to take up water in the different soil layers	m ha-1
LWURT1	Array with root length (diameter < 1 mm) in different soil layers	m ha-1
LWURT2	Array with root length (diameter between 1-2 mm) in different soil layers	m ha-1
MAINFRT	Maintenance respiration coefficient for fine roots	kg CH2O kg-1DM d-1
MAINLV	Maintenance respiration coefficient of leaves	kg CH2O.kg-1 DM.d-1
MAINPD	Maintenance respiration coefficient for pods	kg CH2O kg-1DM d-1
MAINT	Maintenance respiration rate of the crop	kg CH2O.ha-1.d-1
MAINTRT	Maintenance respiration coefficient for taproot	kg CH2O kg-1DM d-1
MAINTS	Maintenance respiration rate of the crop at reference temperature	kg CH2O.ha-1.d-1
MAINWD	Maintenance respiration coefficient for wood	kg CH2O kg-1DM d-1
MAXLAG	Maximum leaf age	d
MINCON	Minimum percentageof carbohydrate reserves	-
MINLAG	Minimum leaf age	d
MINRES	Minimum reserve level	kg CH2O ha-1
NL	Actual number of soil compartments	-
NLA	Number of soil compartments, where from water can be taken up	-
NLBM	Maximum number of layers for local soil arrays	-
NLLM1	Maximum number of layers for local soil arrays	-
NLRT	Maximum number of layers for local soil arrays	-
NLXM	Maximum number of soil compartments	-
NPL	Plant density	plants.m-2
OUTPUT	Flag to indicate if output should be done	-
P	Soil water depletion factor	-
PCEW	Factor that accounts for reduced photosynthesis due to water stress	-
PENMAN	Penman reference value for potential evapotranspiration	mm.d-1
PFRT	Fraction of root dry matter allocated to fine roots	-
PGLA	Length growth parameter of taproot	m d-1
PGLB	Length growth parameter of taproot	d-1
PGLTRT	Relative growth rate of length of taproot	m d-1
PGTRT	Sink related growth of taproot	m d-1
PI	Ratio of circumference to diameter	-
PINT	Intercepted rain	mm
PLTMOD	Name of plant module	-
PRWU	Potential water uptake	mm m-2 root area
PTRANS	Potential transpiration rate derived from Penman evaporation	mm.d-1
PTRT	Fraction of root dry matter allocated to taproot	-
Q10	Factor accounting for increase of maintenance respiration with a 10 degrees C rise temperature	-
QUOTIENT	Intermediate variable	m3
RAIN	Daily amount of rainfall	mm.d-1
RDD	Daily short-wave radiation	J.m-2.d
RESF	Reserve factor	-
RSACT	Actual root shoot ratio	-
RSSET	Setpoint root shoot ratio	-
SAI	Stem area index	-
SLA	Specific leaf area	ha leaf.kg-1 leaf

SPRTL1	Specific root length, root diameter < 1 mm	m kg-1 DM
SPRTL2	Specific root length, root diameter between 1-2 mm	m kg-1 DM
SS	Sink strength	-
SSTB	Table of SS	-
STAGE	Development stage of pods	-
STEMFL	Stem flow	mm d-1
STTIME	Start time of simulation	d
SW	Specific weight of wood	kg m-3
TADRW	Total above-ground dry matter	kg DM.ha-1
TAI	Total leaf and ear area index	ha.ha-1
TAU	Time coefficient	d-1
TAU2	Time coefficient	d-1
TDFRT	Total death rate of fine roots	kg DM ha-1 d-1
TDM	Total dry matter	kg DM ha-1
TDRW	Total crop biomass	kg DM.ha-1
TEFF	Temperature efficiency of maintenance respiration	-
TERMNL	Flag to indicate if simulation is to stop	-
TFALL	Throughfall	mm d-1
TGFRT	Total growth of fine roots, all layers cummulated.	kg DM.ha-1
TIME	Time of simulation	d
TKL	Thickness of soil compartments	m
TMAV	Daily average temperature	degree C
TMAVD	Daily average daily temperature	degree C
TMMN	Daily minimum temperature	degrees C
TMMX	Daily maximum temperature	degrees C
TNASS	Total net CO2 assimilation	kg CO2 ha-1
TRANSC	Characteristic potential transpiration rate	mm d-1
TRANSL	Translocation rate of stem dry matter to storage organs	kg DM.ha-1.d-1
TREF	Reference temperature	degree C
TRTF	Taproot fraction	-
TRWL	Actual transpiration rate per layer	mm.d-1
TSLAIL	Table shade tree LAI	-
TSLAIT	Table shade tree trunk	-
TSS	Total sink strength	-
WCFCX	External array of volumetric water content at field capacity	cm3 H2O.cm-3 soil
WCLQT	Volumetric water content in each soil compartment	cm3 H2O.cm-3 soil
WCSTX	External array of volumetric water content at saturation	cm3 H2O.cm-3 soil
WCWET	Volumetric water content where water logging begins	cm3 H2O.cm-3 soil
WCWPX	External array of volumetric water content at wilting point	cm3 H2O.cm-3 soil
WEIGHT	Weight of leave age classes	kg DM ha-1
WFRT	Weight of fine roots	kg DM ha-1
WFRTI	Initial weight of fine roots	kg DM ha-1
WHAR	Weight of harvest organs	kg DM ha-1
WLVD	Dry weight of dead leaves	kg DM ha-1
WLVG	Dry weight of green leaves	kg DMha-1
WLVI	Initial dry weight of the leaves	kg DM ha-1
WMAX	Maximum weight of roots at depth 0.025 m	kg DM ha-1
WMAXMN	Number of elements in WMAXTB	-
WMAXTB	Table with maximum weights of fine roots at a certain age	kg DM ha-1
WPD	Weight of pods	kg DM ha-1
WPDI	Initial weight of pods	kg DM ha-1
WPOD	Weight of pods	kg DM ha-1
WRES	Weight of reserves	kg CH2O ha-1
WRT	Dry weight of the roots	kg DM ha-1
WSEL	Reduction factor on soil water uptake as function of drought stress	-
WSERT	Auxiliary variable to calculate root extension	-

WTFRT	Total weight of fine roots	kg DM ha-1
WTFRTD	Weight of dead fine roots	kg DM ha-1
WTFRTI	Initial weight of fine roots	kg DM ha-1
WTRT	Weight of tap root	kg DM ha-1
WTRTI	Initial weight of tap root	kg DM ha-1
WWD	Weight of wood	kg DM ha-1
WWDD	Weight of dead wood	kg DM ha-1
WWDI	Initial weight of wood	kg DM ha-1
WWURT	Weight of roots, able to take up water	kg DM ha-1
YIELD	Weight of harvested pods	kg DM ha-1
YRAIN	Annual rainfall	mm
YRDD	Annual radiation	J m-2
YTRANS	Annual transpiration	mm
YYIELD	Yearly weight of harvested pods	kg DM ha-1
ZERO	Zero value	-

Appendix 2

Report of visit to International Fertilizer Development Center- Africa

Lomé - Togo

May 26th – June 24th 1998

Liesje Mommer

student of Wageningen Agricultural University
Department of Theoretical Production Ecology

Contents:

Cocoa production in Togo

Introduction

Cocoa is one of the most important cash crops in West Africa. It is grown largely (>80%) by the small- scale farmers of the region. In 1900, Africa's share of the total world cocoa production was a mere 17%. In 1996 total production from Ivory Coast, Ghana, Cameroon, Nigeria and Togo accounted for over 65 % of the global output (Duguma, 1998). Cocoa has become a leading sub sector in the economic growth and development of these countries. Cocoa was second export product of Togo, immediately following Phosphate Rock (Deuss, 1981). But cocoa shifted down to the 4^{th} place. Export of Phospate (in m $) 83; cotton 75; coffee 21; cocoa 4 (Economist Intelligence Unit, 1996).

The EU has initiated a programme to improve the production of cash crops, the STABEX program. Cocoa is one of the major cash crops, besides coffee and cotton in Togo.

Present situation

The cocoa plantations in Togo are located in the South West part of the country, and occupy an area of
36 500 ha in the Litime region (22 000ha), Kloto (12 500 ha) and Akposso (2 000 ha) (Deuss, 1981, see map). The average yield in the Litime is 290 kg/ha, Kloto 270 kg/ha, Plateau Akposso 140 kg/ha.
The annual average production measured over the years 1979-1983, was 12 300 ton (Addra, 1984).

The cocoa in Togo has become degraded, due to absence of extension and/or rehabilitation of the existing plantations. Now most cocoa plantations in Togo are too old to be profitable.
A cocoa plantation gives a profitable yield until it is 30-35 years old. After that age the yield decreases. In Togo only 30 % is in full production, cocoa plantations between 9 and 30 years old. The other 70 % was planted more than 30 years ago (Deuss, 1981). Jadin & Vaast (1990) wrote that over 92% in the Litime region was planted before 1960.

Since the late 1980's the cocoa sector has been subjected to several major economic shocks. The drastic fall in the world cocoa and other commodity prices contributed to a substantial cut in civil servant salaries, significant (50%) devaluation, freezes on employment and tax hikes. Cocoa farmers and many state employees who lost their jobs responded to the crisis by increasing their activity in food crop production to compensate for lost income (Duguma, 1998). That resulted in a very significant increase in forest clearing, and a neglect of the existing cocoa plantations.

On 80 % of the plantations the caretaker has to do the work, under an unfavorable contract (Jadin & Vaast, 1990). The caretaker gets only one third of the yield and a small piece of land to produce some food crops on. That is not enough profit for all the work that needs been done to maintain a good cocoa plantation.
The major requirements of cocoa are pests and diseases control, shade control, weeding, pruning, harvesting of pods and processing of beans.

The cocoa plantations are divided into small plots. Most of the plantations are less than 1 hectare (Addra, 1984). The sociological aspects of cropping cocoa must not be neglected. The 'family life cycle' interacts with the 'tree life cycle'. Farmers and their trees grow older together. When replanting times come, the farmers are old and lack a labor force (Ruf, 1998). The children have gone to school. If the farmer waits too long to replant, the yields will decline, and the investment in cash and labor will increase.

Rehabilitation programs

There were several renovation programs (SRCC,1987), but they did not succeed. A 1991 survey of the regeneration program of 1987, (120 ha planned, 98 achieved) showed that after 4 years, on average only 32% of the replanted cocoa trees was bearing, and 41 % of the trees was "missing", dead or still used for other purposes. After 4 years a cocoa plantation is expected to be established and to provide an income to the producer. In the case of rehabilitation in Togo, only 28% of the plantations could be considered as established. The trees nearly had formed a closed canopy. It is not surprising that the farmers were unable to start to pay back their investments. The farmers had received the planting materials on long-term credit with a grace period of 4 years. Insecticide spraying the first two years was also guaranteed.

Before the program started the replantation techniques were tested successfully at research stations. How is it possible that introducing these techniques on a small holder farm leads to such contrasting and disappointing results? In literature I found various factors explaining why the same techniques applied on different plots in the same region would lead to different results. But none of these can explain the situation completely.

Pests and diseases
The most severe problem faced by cocoa farmers in West Africa is pest and disease control. In West Africa yield losses ranges from 10 to 80%, in Togo from 30-50% (Duguma, 1998).

Soil fertility
In Togo the soil has been shown to be a determining factor (Jagoret & Jadin, 1993). It has been demonstrated that replanting must be avoided on plantations established on certain types of soil, since mortalities during the dry season can be extremely high. A declining in the yield of cocoa can be explained by the decreasing fertility of the soil under cocoa (Wessel, 1971b). Farmers prefer to start a new cocoa plantation on forestland than to replant on degenerated fallow.

The optimum P-content of the soil for cocoa is 100 mg/kg available P (Jadin & Vaast, 1990). In the Litime region most soils contain less than 15 mg/kg (Dossa, 1991, SOFRECO, 1991). Several experiments in the past, using the method of "soil diagnostics" showed that the P availability increased when applying different kinds of phosphate fertilizers (Jadin 1972; 1987; Loue 1961).

Climate
Another reason for the declining yields of cocoa in Togo could be the change of climate conditions. In 1950 the average annual rainfall was 1 650 mm in the Litime region, in 1980 the average annual rainfall was only 1 350 (SOFRECO, 1991). The harmattan, the tropical wind, blows more severely (Jadin & Vaast, 1990).

Extension services
Differences between farms can also be explained by the variation in cropping practices of the farmers. The farmers did not all use the technical advises in the same way.
Especially weeding is a very important factor; the competition between weeds and young cacao plant is very strong until the canopy closes.
In the Togolese research station the researchers told me that the farmers often do not have the knowledge to reach a good crop production. If this is the case, there is still a big job for the extension services to do.

Cocoa prices
Unlike in recent years cocoa production in agro forestry systems is economically profitable at current prices (Duguma, 1998).
What about government interventions in the cocoa sector in Togo?

But, if cocoa cropping is profitable, why should a farmer not invest labor and equipment in his plantation? The investments for rehabilitation are too big. There are no credit systems that span more than one growing season (pers. com. Breman).

Concluding remarks
It is not easy to conclude if the use of Phosphate Rock on cocoa will be economically feasible. Many aspects have to be taken into account, such as soil type, climate, socio economic factors. But we have to reconise that most of the cocoa plantations in Togo are too old and degenerated to be profitable anyway. Management needs to be improved.

Journal of visit to Institution Recherche du Caféiere et du Cacaoyère (IRCC), in Kpalimé, Togo, from the 3rd until the 6th of June 1998.

Wednesday 3rd of June:
We left IFDC at ten o'clock after waiting for some hours for a travel permit and other things that had to be done. From the car I saw some tropical plants: cassava, oil palm, kapok, eucalyptus, cacao, coconut, baobab. We arrived in Kpalime at twelve o'clock, at IRCC. There we were invited to drink coffee with all the researchers, as if they expected us. But that was not the case: The fax we had sent never arrived at all.
During apres-midi, from 12 until 14.30 the people had a rest and we had lunch on the market place with "Maman". As my travel mates, the driver and Mr Dossa from IFDC were Togolese, I had some pretty African life-experiences.

From 14.30 until 17.30 we did some literature research in the library. What do you call a library? A cupboard with a pile of magazines, papers and annual reports, everything was all mixed up. It was rather hot and fuggy in the library, hard work.
We stayed in hotel "du 30 Août", in Kpalimé.

Thursday 4th of June:

Discussion with Mr Ekwe DOSSA from IRCC:

Question: Planting density, how many cacao trees grow on a hectare? How many shelter trees grow on a hectare? Where do the shade trees grow?
Answer: At the research plantations we have 1 333 cacao trees/ha. The trees are planted in rows. In a row the distance between trees is 2.5 metres and the distance between rows is 3.0 metres. The density of shade trees is around 10 per hectare, they grow where they germinate.

Q: Shade species: What species of shade trees are most common? Is there some knowledge available about the botany of these species?
A: *Terminalia superba* and *Albizzia glaberima*. I never saw a suffering cocoa plantation with these two species as shelter trees. So IRCC thinks that their roots will not compete with the roots of cacao. They grow fast, so you do not have to wait for over 40 years until they provide good shade. Especially the branches of *Albizzia* extend, the radius of the canopy can easily be 20 m. *Albizzia* can reach a height of 30-40 m.
Species that are not suitable, because they spread diseases are *Spondia mombia* and *Ceiba pentandra*.

Q: Is there some knowledge of the plant biomass of a given age? Leaf weight, weight of trunk and branches.
A: IRCC does not get subsidies from the government to do such research. We only count the pods growing directly on the trunk.

Q: How many flushes are there within a year? At what time of the year will the leaves expand? Is the maximum leaf production in March-April? Is there a smaller flush in September? Periodicity of growth?
A: There are always flushes, but there is a peak in leaf expandsion when the rain season starts, the same for flowering of the hybrid varieties. The peak of litter fall is in the dry season and when the harmattan blows. Cacao does not tolerate wind. After pollination, it takes 6 months until the pods are ripe for harvesting.
The cocoa flower is small, tender and has a complex structure (figure 1). Pollinating by wind is not possible. Only very small insects (Family *Ceratopogonidea*, genus f*orcypomia*) can pollinate cacao. Cocoa is underpollinated, so we have to pollinate by hand too: artificial pollination. The hybrids IRCC grows are incompatible within their own variety, so different types of hybrids grow on the IRCC plantations. Traditional Amazon does not have that problem.

Q: What is the average age of most cacao trees? According to literature sources more of 40% of the plantations is older than 60 years. What about the yields of these plantations?
A: 92% of the plantations were in the 60's (Jadin, 1990). So most of the cacao plantations are too old to be profitable. A well maintained cocoa plantation can get a yield of 800 kg dry beans/ha, when the soil is very good and it gets enough rain: 1-1,5 ton/ha.

Q: About fertilizer experiments: Which fertilizer do you use, what rates, types etc.
A: Jadin (1990) found out that the optimum assimilable P availability in the soil is 100 mg/kg. As the cocoa soils in the Litimé region contain less than 15 mg/kg assimilable P, phosphorus fertilizers will have an positive effect on yield in most cases. But, because the nutrition of cocoa is so complex, there are different experimental results, even within a country (Jadin, 1972, IRCC-Togo,1991).

Excursion to the cocoa research fields, experimental plots:
Closed canopy, at shoulder height. Flowers soft pink, growing in a small bundle, directly on the wood. Contrast: rough textured bark and the tender delicate flowers. On average three fruits on a tree, but June is not in the season. No weeds, only fallen leaves on the ground. The top layer of the soils is of mulch, the roots of cocoa intensively occupy this layer.

I tasted a fresh cocoa bean. Mr Dossa smashed the pod, so that the shell broke. Around 60 beans were inside, in a white, slimy stuff. We sucked the white stuff, sweet! Hmm.

Friday 5th of June:

Excursion environment and visit farmer plantations:
We visited small villages around Kpalimé, children came down the road when they heard the car. They shouted: Yovo, yovo! White man, white man!
I encountered the possibilities and impossibilities of tropical agriculture. Slash and burn fields: tropical rainforest has been cleared and only tall trees remained. It is impossible to treat the land with machines, when you walk in between the maize, you sink in the mud until your ankles. Children work on the land with a kind of hoe, little sister or brother on the back.
I saw many tropical crops: cassava, yam, maize, banana, coffee, cacao, rice, oil palm, teak.

We visited some cacao plantations of farmers. This plantations looked sad and wer rather depressive. Nine out of ten pods were rotting, because of the swollen shoot disease. But how could the farmer harvest? The weeds were so tall that you could not enter the plantation.
Do the farmers not have the knowledge to ensure a good cocoa production, as the guide from IRCC sighed, or is cropping of cacao not economically feasible?
Mr Breman commented that I should try to do cross checks and not believe everybody.

Visit to nursery
There are two ways to multiply cacao: vegetative or generative.
In the first case a young, small branches are cut from the "mother plant", on average 20 cm long. The leaves are removed; only 3 halve ones are left. His is put it in the soil, under a plastic sheet, so that the temperature is constant, at 28°C. The seedling receives water three times a day, so that roots will develop easily. Within 6 weeks a new plant grows.
The second method is less work: a seed is put in a bag with soil.

Discussion with Mr KOUDJEGA from IRCC:
About fertilizer requirements of cacao. Doses and type of fertilizers.
At IRCC they tested the method of "diagnostic sol", they have two experimental plots both located in the Litimé region, called L4-R5 and L17.

The treatments for the different sites "with fertilizer" were (gifts per tree):

L4-R5, planted in 1974:
1977: 350 g phosphate rock (PR), 100 g potassium chloride, 150 g tri super phosphate(TSP)
1978: 6x50 g ammonium phosphate, 200 g slaked lime
1979: 200 g lime
1980: -
1981: 250 g TSP, 150 g potassium chloride
1982: 250 g TSP, 150 g potassium chloride
1983: -
1984: 50 g PR from Togo, 50 g lime, 60 g 15-15-15, 150 g potassium chloride
1985: 50 g PR from Togo, 150 g potassium chloride
1986: no data found
1987: 250 g TSP
1988: 100 g potassium chloride
1990: 50 g TSP, 2x100 g potassium chloride

L17, planted in 1985:
1986: 100 g TSP, 50 g 15-15-15
1987: no data found
1988: 100 g TSP, 50 g potassium chloride
1989: 100 g TSP, 100 g potassium chloride
1990: 100 g TSP, 2x100 g potassium chloride

Yield (kg dry beans/ha):

L4-R5:

year	without fertilizer	with fertilizer
1987	1239	1628
1988	1629	2481
1989	676	1099
1990	658	1171
Σ	4202	6379
μ	1050	1595

The differences between the treatments in the years 1988-90 are significant ($P<0.05$).

L17:

year	without fertilizer	with fertilizer
1987	-	-
1988	201	302
1989	54	76
1990	101	175
Σ	357	554
μ	119	184

Only the difference between the treatments in 1988 is significant ($P<0.05$).
It must be noted that this plantation is very young, planted in 1985.

(IRCC-Togo, 1988,1991, annual reports)

Saturday 6th of June

After a visit to the market, which was as busy as an ant hill, we returned to Lomé.

Difference between a farmers and a research plantation

Photo App 2.1: Farmers plantation in Togo, Kpalimé, June 1998; Liesje Mommer

Photo App 2.2: Plantation of CRIG, Ghana; June 1998; Liesje Mommer

Difference between plantations of IRCC-Togo and CRIG

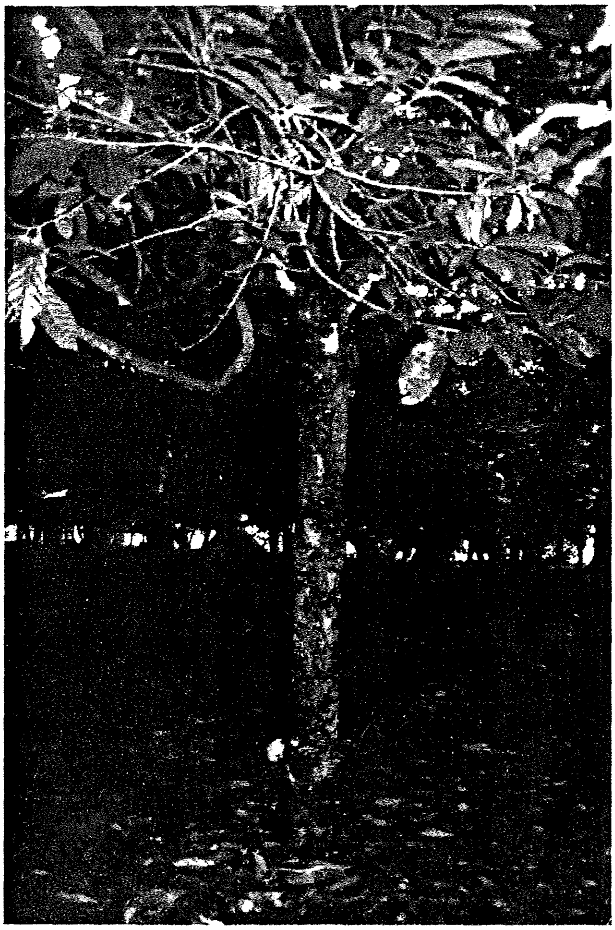
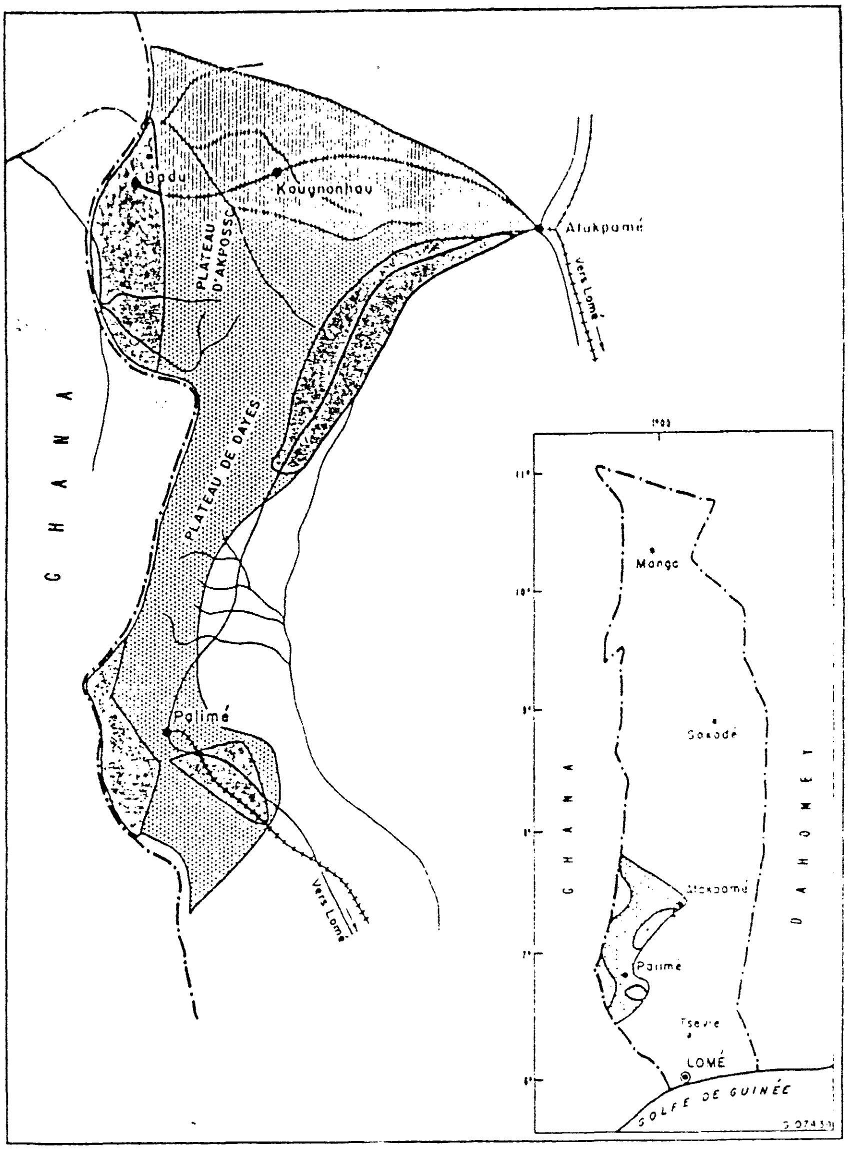


Photo App 2.3: Tree at IRCC plantation
June 1998; Liesje Mommer

Photo App 2.4 Tree at CRIG plantation
June 1998; Liesje Mommer

Cocoa producing areas in Togo



Dense plantations

Scattered plantations

Journal of visit to Cocoa Research Institute of Ghana (CRIG), New Tafo, from the 9th until the 13th of June 1998.

Tuesday 9th of June:
We travelled from Lomé to Tafo, 288 km. Departure in Lome at 8.30 AM, arrival at CRIG at 3.00 PM. We moved into the CRIG guesthouse.

Wednesday 10th of June:

In the morning, from 7.30 until 12.30:

Discussion with Dr. G.K. Owusu, director; Dr. E.B. Frimpong, physiologist; Dr. Asanti, agricultural economist; Dr. M.R. Appiah, agronomist.

* Introduction – Mr. B. Honfoga from IFDC and I gave a presentation about the reason of our visit to CRIG. The introduction included the possibilities of modelling cocoa growth, basic principles of system analysis and theoretical production ecology. I explained that I am trying to figure out the potential yield of cacao and the yield under water limited conditions. Simulation is a way to figure out the gaps in knowledge. Mr Honfoga sketched in broad lines the objectives of the STABEX program.

* Why do the farmers plantations in Togo are in such a bad condition? Is there a lack of knowledge? Is it because the farmers do not know how to produce a high yield? Is it not profitable to crop cocoa? Are the world market prices too low?

In Ghana the plantations are in the same state as they in Togo are. Cocoa is a not an easy crop. During the first four years, besides the financial investments, the farmer has to put in a lot of labor, but without getting back any profits. Weeding takes a lot of time, until the canopy has closed. Control of capsids, which cause a lot of leaf fall, is necessary to keep a closed canopy. Replanting trees after a local disaster is very important, for the same reason. Pruning cacao is a hard job, because the hybrid the farmers use, has a lot of branches. When pruning is not done properly, the black pod disease will have a chance.
CRIG experience is that farmers are willing to listen, but that the benefits of cropping cocoa now are too low. There are some experiments with fertilizers on farmer plantations. In these experiments the fertilizers are free of charge, so the farmers only have to observe what is happening, count the pods and observe the encouraging results. Normally farmers do not have the money to invest in fertilizers.
The government fixes the price of cocoa, a farmer gets only 1800 cedis per kg dry beans. The cocoa market must liberalize, in small stages, then it will be more profitable to crop cocoa.

There is also the typical socio-economic system for Ghana and Togo that needs to be taken into account. This is the system of the land owner and the caretaker. The latter has to manage the plantation and do all the work. He gets only one third of the harvest and a small piece of land to produce some food crops on. That is not enough profit for all the work that needs to be done to maintain a good cocoa plantation. Often they weed only twice a year, instead of three times. So this is not a good system.

Do you think the system will change?

When the farmer uses fertilizer, then the yield will be bigger, the one-third part too, and labor will be more satisfying. Fertilizers also mean more weed growth. Then, it will be more important to have knowledge about how to maintain a good cocoa plantation.

* Some notes on Phosphate Rock (PR): consists of P, Mg, Ca and Silica. The availability of P in PR is low. P is not easy soluble. Applying PR over a long period will be beneficial, especially for

perennial crops. They have the advantage over annuals hat they grow for many years on the same place. When the soil is acidic in nature, using PR will increase pH. It has a liming agent. The rate of P-uptake is not easy to calculate, because of the slow release over many years. CRIG does not have any experience with PR. They are rather interested in the results of IFDC.

*List of jobs, needed to be done to maintain a well cropping cocoa plantation:
-Control capsids: spraying insecticide four times a year, in August, September, October and December. The farmer has to use Undin and Gammalin alternatively, to prevent resistance.
-Black pod control: from late May or early June every three weeks up till October. Black pods need to be removed.
-Pruning, jargon for cutting off branches, twice a year.
-Shade control: The shade trees need maintaining as well, once per three years.
-Mistletoe, a parasitic plant needs removing, once a year.
-Applying fertilizer in May, when the rain season has started: 120 kg P_2O_5 per ha, 80 kg K_2O per ha.

<u>Discussion with Dr. E. B. Frimpong, physiologist.</u>

*About planting density, how many cacao trees grow on a hectare?
1000 till 1010 cacao trees grow per hectare, they grow 8 feet apart.

* Shade species: What species of shade trees are most common?
Is there some knowledge available about the botany of these species? Root distribution, leaf distribution, leaf size, architecture of canopy? Where do the shade trees grow in the plantation? How many shade trees grow on a hectare?
CRIG distinguishes between temporary and permanent shade.
For young cocoa up to three years old, temporary shade is needed. Often cassava, plantains (cooking bananas) and Gliricidia are used. The advantage of the first two species is that they are food crops, so the farmer will have an income from these species until cocoa produces pods.
For the permanent shade trees they use Terminalia spp. There are 60 – 66 trees per ha, 30 feet apart from each other. These are fast growing species, present in the rainforest. On plantations these trees are left-overs after clearing the forest. CRIG does not grow Albizzia spp, because of its root distribution. The roots of Albizzia and cocoa are both in the top layer of the soil. (Personal comment by E.B.Frimpong) The roots of Terminalia ivorensis are known to reach a bigger rooting depth.

*Is there some knowledge of the plant biomass at a given age? Leaf weight, weight of trunk and branches. Did you cut a tree and weigh the different parts?
In Cameroon, Dr.Boyer did measurements on the LAI, did you do those kinds of measurements?
CRIG never did not such experiments. In the past we measured LAI, and we found out that LAI was constantly around 4.

* About water limitation: Did you do any kind of experiments to increase the knowledge of the water relations of cocoa? Cacao is rather sensitive for drought, do you know what the loss of yield will be when the plants suffer from water shortage?
CRIG tested around 700 clones in the greenhouse and the field to stydy how growth and yield are affected when suffering by water shortage. CRIG tried to select the tolerant types. They studied the roots; plant biomass; photosynthetic rate; water use efficiency, gram water needed to produce one gram of biomass; leaf adaptations. Clones with high SLW (Specific Leaf Weight, gram of leaf weight per area of leaf) and small leaves do better under water shortage compared to clones which have the opposite. The development of a deep and extensive root system is a structural feature which enhances plants the ability to endure external water stress. Factors which limit cuticular transpiration is such a structural feature too. They also did measurements at the cellular level. Plants put under water stress produced a lot of proline. It seems that hybrids with a higher tolerance produce more proline.

Adaptations exist to escape or delay drought damage. (Bonaparte, 1994)

* Growth periodicity: what are the theories about that?
For mature cacao trees solar radiation is the driving factor. The carbohydrate level follows this cycle.
Only 2-6 % of the flowers will become a pod. Cherelle wilting is a factor which influences yield reduction, and is greater when there is less water.
For coffee the hydro-theory holds. The buds will form, but if no rain comes, all the buds will dry.

In the afternoon, from 13.30 till 16.30:

<u>Excursion to "square mile" with experimental plots.</u>
*see map of the plantation.

* I noticed the difference between Amelonado and Amazon-cacao and various hybrids.
Amelonado produces less litter fall, because it has less branches. Amelonado trees are taller, the stems are not so big. The jorquette starts around 3 m, while the jorquette of many hybrides is at shoulder height. Branch spreading of the hybrids is more horizontal, the canopy closes easier.
The quality of the Amelonado beans is best, but Amelonado starts cropping only after a rather long "juvenile" period of 8 years. Amazon starts yielding after 4 years, some hybrids after 2 years.
This is what farmers want: Pod setting as soon as possible, because they want their investments back.
* Cocoa replanting experiment: they cut the old cocoa trees down, up to 15 cm. But they left the shade trees, Glyricidia. The old cocoa trees sprouted again, and are growing into new trees. Like Dutch pruning willow trees.
* Coconut-Cocoa inter cropping experiment showed good results. The combination of these trees is good for controlling pests, and the farmer has double profit. This combination however is not so much used in Ghana; much more in Malaysia and Ivory Coast.
* Often 11-17 pods on a tree, much more than I saw at IRCC-Togo, there I thought 3 was a lot.

Thursday 11th of June:

In the morning:
I did some literature research in the library, I have read the Ghana Journal of Agriculture, some papers of Tropical Agriculture, report on the drought resistance thrust.

<u>Discussion with Dr. M.R. Appiah, agronomist and Dr. Ofori Frimpong, soil scientist</u>

* History of fertilizer trials on cocoa by CRIG:
CRIG was established to do research on avoiding pests and diseases in cocoa. Cocoa was grown on rather fertile clearly felled land. After some years however, the yields began to decline. So CRIG started experimenting different types of fertilizer, rates of application and time of application. In the early sixties N-application caused a decline of yield, while P- and K-fertilizers caused a rise in the cocoa production.

The farmers began to grow hybrid cacao, a combination between the fast growing, early yielding Amazon and sustainable, slowly growing Amelonado. This hybrid needs a lot of nutrients: N, P, K. Now, at the end of the 90-ties there is no new land left, and cocoa is growing on old land. Within a few years there will be no crop if the farmers do not apply fertilizers.

CRIG tested three moments of fertilizer application: March-April, May-June, November-December. There was a very good response on the first trial, a good response on the second and none on the third. This is easy to understand: it all depends on the rain season and the availability of water, so that the fertilizer can solve and be taken up by the plant.

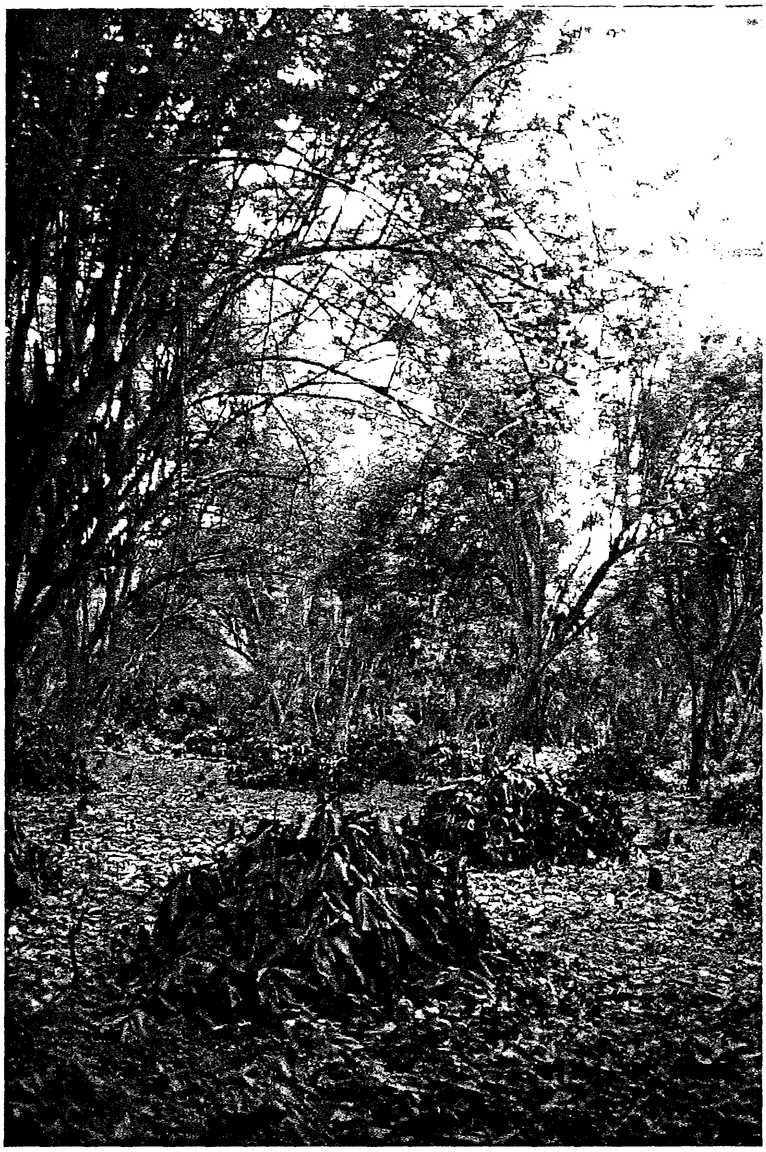


Photo App 2.5 Regeneration of cocoa plantation. The standing trees are shade trees, Glyricidia spp. The cocoa trees are cut of like pruning willow trees in Holland. June 1998; Liesje Mommer.

Rates of fertilizers:
CRIG recommends to farmers to use the following doses of P- and K-fertilizers: 80-120 kg P2O5 per ha, 50-80 kg K2O per ha.

* Transfer of knowledge to farmers:
Until now no farmer applies fertilizers. They do not have the money to invest in fertilizers. Also, they are not aware of the P-deficiency of the soil. Farmers think: "I use pesticides, that will bring the yield up." They do not think of the whole system, which includes the soil.
Soil improvements is needed. The Ghana Cocoa Board, the cocoa extension service, encourages farmers to use fertilizers. But often their attempts fail because of the costs involved. A long as the farmers do not understand the benefits, they will not apply fertilizers. So there is still a big job for the Ghana Cocoa Board, which provides the farmers with information.

The famous shade and manurial experiment done by CRIG researchers in the 60's, showed a big gap between a farmer and a research plantation (see figure 2.2.2). Without applying fertilizer and without removing shade Ahenkorah (1974) harvested three times as much as the national average. Knowlegde about how to maintain a good plantation is very important. The experiment showed that without any financial investments, just time cocoa production can easily be doubled.

* Do you have a description of the soil characteristics, on which you cultivate cacao? Can you tell something about the degree of deforestation in Ghana?

In the Ghanaian classification the soils are called: Forest Ochrosols, in the FAO classification Rhodic Ferralsols. Most cacao is cropped in the western part of Ghana. The farmers have moved to virgin land in the West. Most young cacao grows there. The pH of these soils is around neutral, 6-6.5. They are less acidic than the Togolese soils, pH (water) between 5 and 6 (SOFRECO, 1991).

For three decades Ghana's forests in the Ashanti, Brong Ahafo, Western and Eastern regions, have been continuously commercially exploited without simultaneous organized replenishment of the forest resources. The magnitude of deforestation is enormous. It is a reduction of areas suitable for cocoa production. Bush fires in the 1980's contributed to the extent and intensity of the deforestation. Because of the low cocoa prices many farmers concerted to food farms, an exercise which necessitated further destruction of the forest. The disappearance of the forest affected the macro and microclimate of cocoa growing areas. The intensive deforestation for timber, fuel wood, food crop production is not favourable for for cocoa growth. Cocoa does not thrive where there is a long dry period and does not tolerate wind.

* In the last two decades seems to be a climatic change in West African sub region. The northern and southern limits of cocoa growing areas in Ghana are indicated by the isohyetal contour of 254 mm of rain between November and March.
On continental scale there is a change in main seasonal rainfall (1930-1960,1961-1990):
    Increase in boreal summer rains (June-July-August) + 0.4 mm/d (+10%)
    Decrease in austral summer rains (December-January-February) – 0.2mm/d (-15%)
    Decrease in autumn rains (September-October-November) > - 0.4mm/d
The seasonal rainfall is determined by the dominant role of Inter Tropical Convergence Zone.
Increased seasonality in southern coastal region, decreased seasonality in eastern region.
Possible courses:
    Related to land cover changes within the continent.
    Changed global ocean circulation and sea surface temperatures.
    Changing composition of global atmosphere.
(Bonaparte, 1994)

In the Afternoon:

I visited the entomology lab, studied "mealy bug" experiment of two Italian students, trying to introduce the natural enemy of the mealy bug. Walked through the CRIG plantations and garden with other Theobroma species with two Italian students.

Friday 12th of June:

7.30 literature review in library
8.30 Conversation with Drs. Osei Brusu , specialist on shade

* What species of shade trees are most common?
Terminalia, Glyricidia and coconut are the best permanent shade trees. Glyricidia gives a bit of a problem sometimes, because the canopy reaches the same height as the cacao canopy. But it is very good to create uniformity of environment and it is not possible to get adequate amounts of other shade species. CRIG, or the Ghana Cocoa board, recommend these species to farmers. But in reality, a farmer often starts a plantation after cutting the forest, then the big forest trees act as shade species.

* Is there some knowledge available about the botany of the shade species? Root distribution, leaf distribution, leaf size, architecture of canopy?

Cocoa-Cordia
Leaf biomass 2040 kg/ha
Root biomass 2720 kg/ha
Ratio roots/leaves 1.33 (Ewel et. al., 1982)

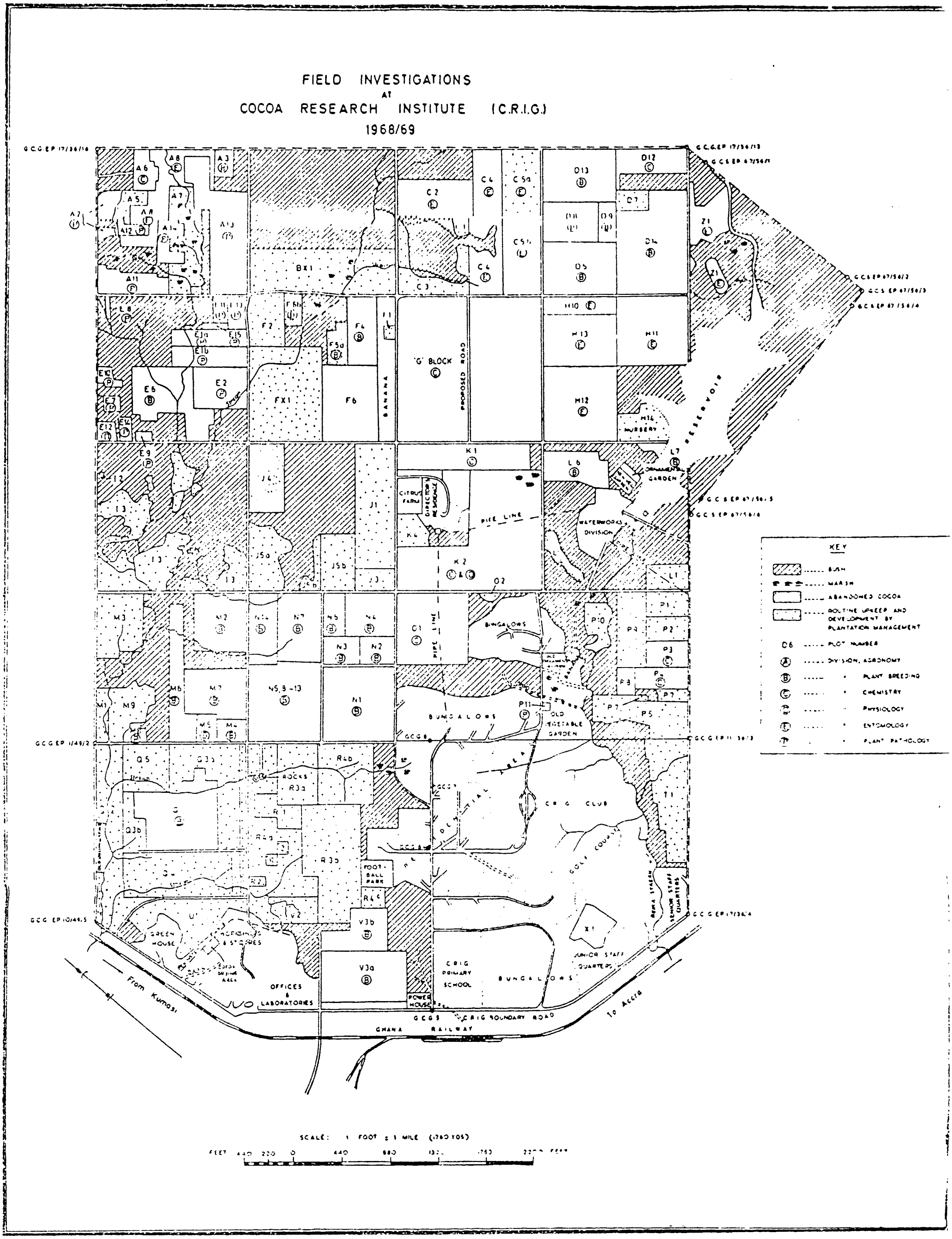
Gliricidia sepium : Dry biomass yield (5.50 t/ha/yr), N yield (169 kg N/ha/yr,) of prunings of this woody legume species, grown in alley cropping systems in the forest-savanna transition in southern Nigeria. Prunings did not include woody material. (Source: Juo and Kang, 1988)

* Cassava-cocoa inter cropping: When experiments started on the profitability of intercropping cacao and food crops. The researchers hypothesized that it would exhaust the soil. Cassava is a plant that invests in the roots, so cacao would not get enough nutrients. But after five years of observation there seems to be no negative effect. The soil quality remains constant and the farmers use the same amount of fertilizer as they have always done for cassava. So this is a benefit for he farmer. Intercropping of maize-cassava-cacao is best in economic terms.

10.00 Visit to cocoa farmer, using CRIG-techniques on his farm. This plantation looked quite well. There were no weeds, closed canopy, many fruits growing, no black pods. I gave the farmer a pat on the back and he smiled from ear to ear.
15.00 Visit to fermentation process. Pods broken on a heap; slimy, white beans fermenting under banana leaves; beans, five days fermented already, had turn brown, the smell of cocoa had appeared, were drying in the sun. I tasted cocoa-jam (not chocolate spread), they make it from the sweet, white, slimy stuff around the beans. CRIG produces cocoa-gin too. They use the shell of the fruit to make soap.
18.00 drink in the CRIG club with Mr Honfoga, Dr. G.K. Owusu, Italian students and several other men.

Saturday 13th of June:

Departure to Lome at 8.00 A.M., after breakfast. The Italian students traveled with us to Accra. We arrived at home at 2.15 PM.


FIELD INVESTIGATIONS
AT
COCOA RESEARCH INSTITUTE (C.R.I.G.)
1968/69
KEY
BUSH
MARSH
ABANDONED COCOA
ROUTINE UPKEEP AND DEVELOPMENT BY PLANTATION MANAGEMENT
PLOT NUMBER
DIVISION, AGRONOMY
PLANT BREEDING
CHEMISTRY
PHYSIOLOGY
ENTOMOLOGY
PLANT PATHOLOGY
'G' BLOCK
PROPOSED ROAD
BANANA
NURSERY
RESERVOIR
ORNAMENTAL GARDEN
CITRUS FARM
PIPE LINE
WATERWORKS DIVISION
BUNGALOWS
OLD VEGETABLE GARDEN
ROCKS
C.R.I.G. CLUB
GOLF COURSE
FOOT BALL PARK
GREEN HOUSE
OFFICES & LABORATORIES
POWER HOUSE
C.R.I.G. PRIMARY SCHOOL
JUNIOR STAFF QUARTERS
SENIOR STAFF QUARTERS
From Kumasi
To Accra
C.R.I.G. BOUNDARY ROAD
GHANA RAILWAY
SCALE: 1 FOOT = 1 MILE (1760 YDS)

EXPERIMENTAL AREAS

PLANTATION MANAGEMENT

A5	Root growth experiment planted in 1955. (Abandoned).
A7	Amazon hybrids planted in 1961.
A8	Amazon hybrids planted in 1961.
B×1	Cola plot planted in 1967.
C5a	Herbicide experiment planted in 1961.
D7	Amazon pruning trial planted in 1956. (Abandoned).
F2	Time of shade removal trial planted in 1962. (Abandoned)
F1	Abandoned village site establishment planted in 1957.
J3	Clonal material (Pa35 & Na32) planted in 1960.
J5 a & b, K4, M9, P10 ..	Irregular cocoa present when the station was acquired.
L1/P1	Basal chupon growth experiment planted in 1948/49. (Abandoned).
M1	Old clone collection planted in 1946.
M3	Routine planting — 1947.
P2	Amelonado pruning trial planted in 1950. Changed to Flower counts experiment.
P5	Amelonado—Routine planting—1953.
P7	Amazon—Routine planting—1955.
P8	Amazon—Routine planting—1957.
P9	Variety trial planted in 1957 (Abandoned).
Q2	Cocoa of various types and ages on an irregular site including plant breeding, old cocoa nursery, propagators and clonal nursery planted in 1952/64.
Q3, R4, U1, V2	Parts of original Old Station cocoa (including parts of abandoned 3rd, 4th, 6th and 7th P.T.As.) Under long term recording in quarter acre sections.
Q5	Routine planting—Amazon hybrids planted in 1960.
Q4, R3	Regeneration trial—1962 (Abandoned).
R1	Ex. 5th P.T.A.—1942.
T1	Amelonado—Routine planting—1960.
H14	Main Station Cocoa Nursery.

PLANT BREEDING INVESTIGATIONS

A3	Clone collections: budded clones—1952–53.
D5	9th Progeny trial: Series II varieties planted in 1954.
D8	3rd Clonal trial planted in 1956: Amazon and two local Trinitario clones.
D9	9th P.T.A. (progenies from D5) planted in 1957.
D13	Series III variety trial planted in 1963.
D14	Variety trial—1965.
E6	Series IV variety trial planted in 1963.
F4	Series V variety trial planted in 1963.
F5 a & b ..	Extra Reps. of the E6 trial planted in 1963 (Abandoned).
M2	1st Clonal trial planted in 1947: Local Trinitario selections.
M4	Various genetic observation planted in 1960.
M5	Various genetic observation planted in 1961.
M6	Seed production plots planted in 1961.
M7	Trial of Amazon progenies and two series II varieties planted in 1962.
N1 & N3	Trinidad introductions planted in 1945–46.
N2	*Theobroma* species collection planted in 1946.
N4	2nd Clonal trial: Local Trinitario selections planted in 1948
N5	Multiplication plot planted in 1948–49.
N6	Observation and polyploid plots planted in 1951.
N7 ..	8th Progeny trial planted in 1952 (various cocoa types and accompanying plots).
N8	Colombian introductions planted in 1956.
N9	F1, F2 & F3 trial planted in 1958.
N13	Expt. 1–4: several expts. on small plots planted in 1959.
N14	Strip planting mainly of series II varieties.
N (Msc.)	Miscellaneous small collections including N7a, 10, 11 & 12.
Q1	2nd Progeny trial: Local Trinitario selections planted in 1942.
V3 a & b ..	New clone collections planted in 1967–68 respectively.

L6	New clone collections (introduced clonal material from Miami Florida). Planted in June, 1967.
L7	Cocoa nursery.

PATHOLOGY

A2	Virus tolerant material planted in 1950.
A11	Rate of virus spread, etc. planted in 1966–67.
A12	Virus tolerance trial (A2 material) planted in 1967
A13	Virus tolerance trial, to be planted in 1969.
A14	Virus resistance trial to be planted in 1969.
E1	Virulent 1A isolate of CSSV on Amazon planted in 1959.
E1	Collection of virus tolerant cocoa types planted in 1959.
E2	Virus tolerance and resistance trial planted in 1960.
E7	Virus tolerance experiment (split whole seedlings) planted in 1963.
E8	Short term investigation on stem pitting.
E9	Virus museum.
E10	Cuttings—Virus tolerance test of breeding material planted in 1967.
E11	Virus tolerance trial.
E13	Virus tolerance trial to be planted in 1969.
E14	Rate of virus spread in susceptible and tolerant cocoa to be planted in 1969.
E15	Virus-infected Nanay collection, to be planted in 1969.
M8	Alternative host nursery.
P11	Cocoa nursery.

CHEMISTRY

A6	Amazon—4K × 2^3NPKMg factorial in April, 1964, (planted in 1956).
D12	Soil test 4K × 2P planted in 1961.
G/Block	To be planted in 1969 (Hybrids).
K1	Amelonado, shade and manurial trial (planted in 1947).
K2–01	Amazon shade, 3N × 3P × 3K planted in 1959.
P3 & P4	Soil test, 4P × 2K planted in 1951–52.

ENTOMOLOGY

A8	Pollination experiment
C2	Ecological trial.
C4	Capsid population studies.
C5 b	Coppicing and caged experiment.
H10	Variety and fertilizer trial changed to systemic insecticide trial—I.C.R.T.
H11	Systemic insecticide trial—I.C.R.T.
H12, H13	Establishment trial planted in 1968.
Z1	Ant studies.

PHYSIOLOGY

K2–01	Amazon shade, 3N × 3 P × 3K planted in 1959.
E12	Isotopes experiment (planted in 1968).

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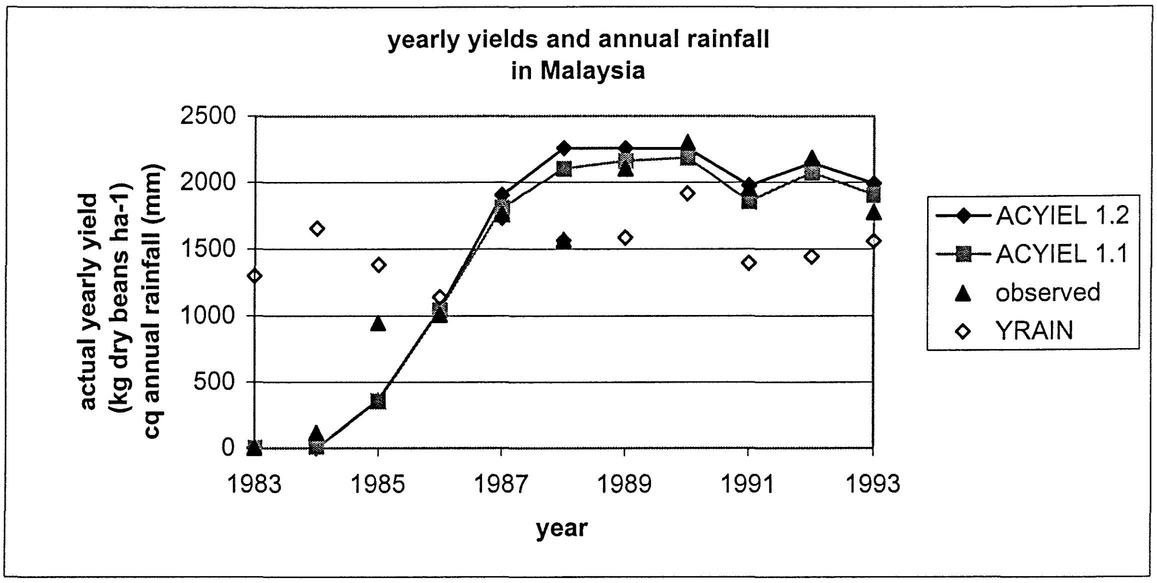
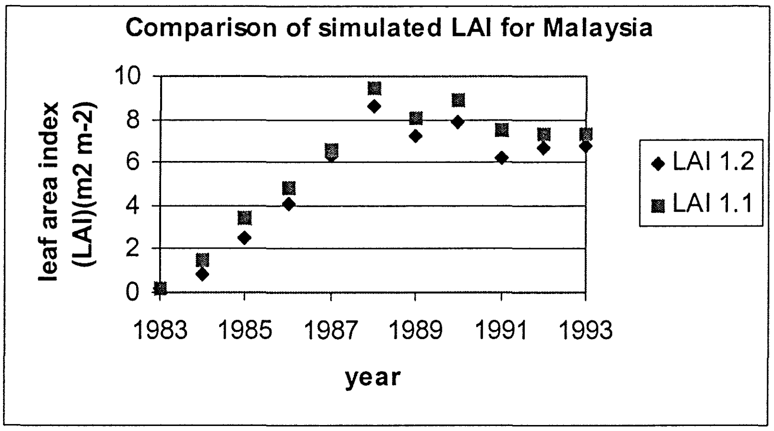
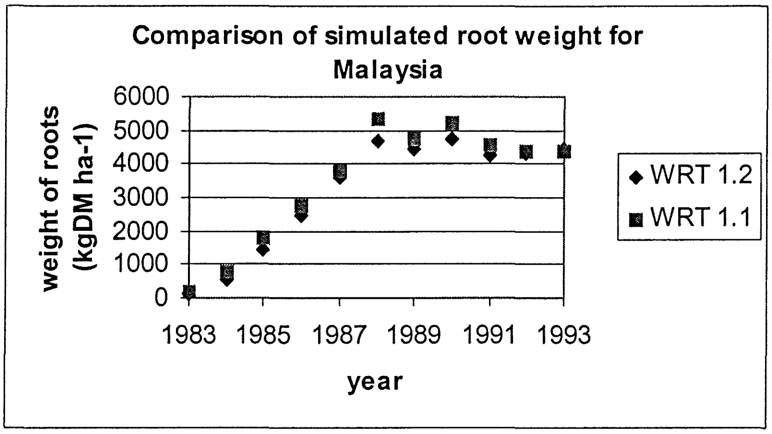
Appendix3



Appendix 3a: Simulated and observed yields in Malaysia and observed rain fall.

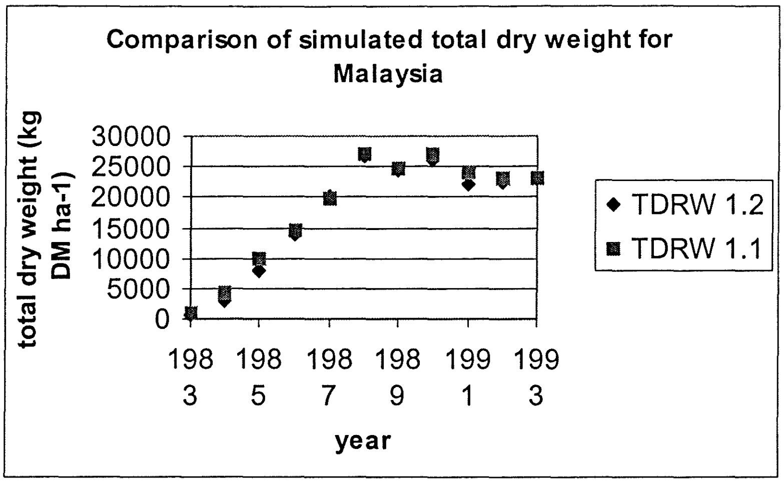


Appendix 3b: Comparison of simulated LAI in Malaysia.

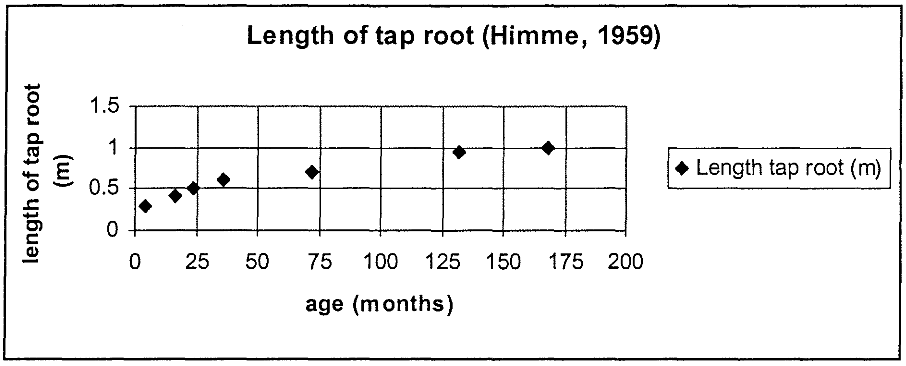


Appendix 3c: Comparison of simulated weight of the roots in Malaysia.

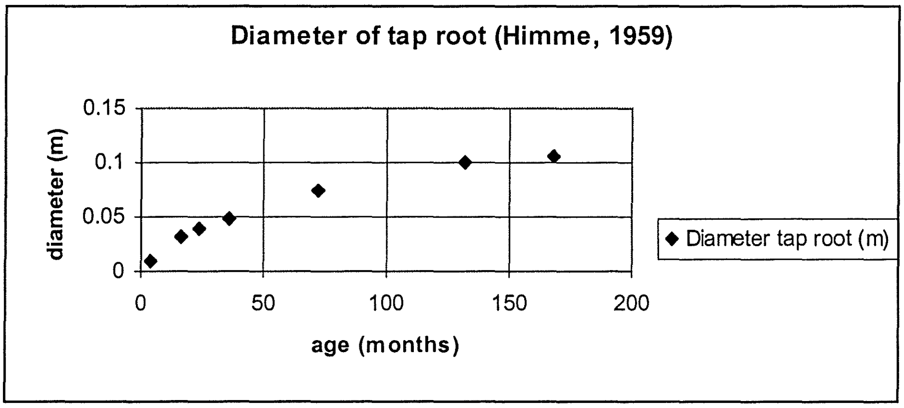
Appendix3



Appendix 3d: Comparison of simulated total dry weight in Malaysia.



Appendix 3e: The length of the taproot shows a negative exponential relation with age.



Appendix 3f: The diameter of the taproot shows a negative exponential relation with age.

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