A physiological production model for cacao:

Results of model simulations

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February 2002

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Copies of related reports on CASE2 (User's manual and Model description and technical program manual) as well as the CASE2 program, are available from the Plant Production Systems group office at the above e-mail address.

This report has been produced within the framework of the "Collaborative research for an agro-technological growth and quality model of cocoa" of the Dutch Cocoa Association (NVC) and Wageningen University. Financial support for this study was obtained from the Dutch cocoa processing industry, the Dutch Ministry of Economic Affairs and Wageningen University.

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Executive summary

- Purposes

This report is produced within the framework of a research programme on modelling of growth, yield and quality of cocoa. The overall objective of this programme is to increase the understanding of cocoa production in relation to environmental conditions and cropping systems. A better understanding of cocoa production systems may assist to improve cocoa production systems in producing countries. To this end, a physiological model (CASE2) has been developed that simulates cocoa growth and yield for different weather and soil conditions and cropping systems.

This report introduces the CAcao Simulation Engine for water-limited production (CASE2, version 2.2) in a non-technical way and presents simulation results obtained with the model. The CASE2 simulation model serves the following purposes: (1) To estimate cocoa yields in relation to weather and soil conditions and cropping systems; (2) to obtain insight in factors determining production; (3) to integrate existing knowledge on the physiology and morphology of cacao trees; and (4) to identify gaps in knowledge on the physiological basis for estimating cocoa growth and yield.

- Model description

The CASE2 simulation model uses information on daily weather (radiation, rain, vapour pressure and temperature), soil characteristics (texture classes of different soil layers), plant characteristics (physiological and morphological characteristics) and cropping system (tree density, tree age and shade regime) to estimate growth and yield of cacao trees in a plantation. This information is processed in different parts of the model. For example, data on radiation, shade regime, plant morphology and physiology is used to quantify photosynthesis of the cacao trees. Information on rainfall, vapour pressure, temperature, soil characteristics and root distribution is applied for the calculation of water uptake and loss. Model calculations on bean yield are based on information about the distribution of total tree weight over the different plant parts, the ripening period of the fruits and the ambient temperature.

Physiological processes (light interception, photosynthesis, maintenance respiration, growth and water uptake) are described and quantified in detail in the model. Model output is provided for a large number of parameters, among which the weight of plant parts, the total leaf area, the root distribution and the bean yield of the model cacao trees.

- Results of model simulations

Comparison of model output on bean yield, standing biomass, biomass production and leaf area with observed values on these parameters shows that simulated values approach real values well. This suggests that cacao physiology and morphology are correctly described in the model and that values for the input parameters are realistic.

A sensitivity analysis of the model shows that the model is rather robust to changes in the values of input parameters. A 10%-change in the value of input parameters generally results in a smaller relative change in yield or biomass production. Input parameters to which model output is most sensitive are related to both the harvestable component of the tree and to the photosynthetic capacity of the tree. That is, increased cocoa production can be achieved both by improving the efficiency of bean production by a cacao tree and by improving its total photosynthesis.

Scenario studies show considerable differences in estimated yields when using weather information of 18 locations in eight countries (Brazil, Costa Rica, Ghana, Indonesia, Ivory Coast, Malaysia, Philippines and Papua New Guinea). The annual yield averaged over 10 simulation years ranges from 3800 to 6100 kg ha^{-1} y^{-1} for model plantations of 1000 trees ha^{-1} on favourable soils with *ca.* 10% shading and an initial tree age of 4.1 years. About half of this variation can be explained by

the combination of rainfall and radiation. Thus, when average rainfall and radiation is available, a first estimate of the attainable bean yield can be obtained using a simple regression formula. Large part of the remaining variation is likely to be due to differences in the distribution of rain during the year. Running the model with different soil types leads to notable differences in bean yield and biomass production in locations with a long dry season. Water limitation causes reductions in simulated bean yield of <1 to 60% depending on weather conditions and soil type. Applying different shade levels in the model also considerably affects simulated plant growth and bean yield. Shading of >60% caused strong declines in simulated bean yield compared to a situation without shade. Changes in initial size of the model trees have a moderate effect on model output, especially when choosing ages of 3-10 years.

- Recommendations

The CASE2 model has been developed using existing knowledge on physiology and morphology of the cacao tree. The current model makes use of almost all published and relevant information on the cacao tree. Further model development therefore requires new insights into cacao growth and new estimates for important model input parameters. Especially studies that relate physiological processes to the environment (shading, seasonal water availability) are of importance.

Given the finding that a large part of the inter-location variation in simulated bean yield is due to differences in the distribution of rain during the year, it is recommended that the effects of water shortage on plant physiology and morphology are studied in detail. Using results of such a study, the modelling of water shortage effects in CASE2 can be evaluated and adapted, if necessary.

Another field for further study and model development is shading. In the current version of CASE2 high shading levels cause strong reduction in yield, but this yield reduction is not well validated. Additional insight in physiological and morphological shade adaptations of cacao trees is required, and field measurements may be used to compare yield reduction due to shading with model simulations.

A third topic for study and model development is the dynamics of leaves in cacao trees. The relation between leaf life span on the one hand and water availability, light level and position in the canopy of the other is not well understood. As light and water availability vary largely among locations and cropping systems, it is important to understand these relations and to evaluate the consequences for model output.

Finally, the current version of CASE2 does not cope with the limitation of nutrients. Inclusion of this aspect in the model would allow for the estimation of additional nutrient requirements of different cropping systems at different locations and on different soil types. However, it requires physiological insight into the uptake, use and re-allocation of nutrients which is mostly unavailable. Inclusion of nutrients in the present model would therefore require extensive field studies to obtain better insight in the processes involved.

Preface

This report presents simulation results of a physiological model for cacao growth and yield (CASE2, version 2.2). It is one of the results of a cocoa research and modelling programme of Wageningen University on behalf of the Dutch Cocoa Association (NCV)[1]. The current version of the model has been developed in the period April-December 2001. Model simulations of which results are presented in this report were also carried out during this period.

This document contains an introduction to the model and provides some guidance in the interpretation of model results. Furthermore, it presents results of scenario studies that compare growth and yield estimates for different climates, soil types and cropping systems. A user-friendly Windows-based version of the model will be made available early 2002, together with a user's manual. A technical reference manual containing detailed program information and one or more scientific publications are also foreseen for early 2002.

Several people have contributed to the realisation of this report. Wouter Gerritsma and Liesje Mommer developed previous versions of the model. Jan Goudriaan provided valuable input for model development. Wouter Gerritsma gave important reference to literature and commented on model development. Rudy Rabbinge provided overall guidance during this phase of the project. Weather data were kindly made available by various persons at the Department of Plant Sciences and Plant Research International (both at Wageningen University and Research Centre). Financial support was obtained from the Dutch Cocoa Association (NCV), the Dutch Ministry of Economic Affairs, and the Plant Production Systems group at Wageningen University. All contributions are gratefully acknowledged.

Wageningen, February 2002

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1 *"Collective research for an agro-technical growth and quality model of cocoa"*

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1. Introduction to the report

1.1 Purpose of the report

This report is produced within the framework of a research programme on modelling of growth, yield and quality of cocoa. The overall objective of this programme is to increase the understanding of cocoa production in relation to environmental conditions and cropping systems. A better understanding of cocoa production systems may assist in improving cocoa production systems in producing countries. To this end, a model (CASE2) has been developed that simulates cocoa production depending on weather and soil conditions and the cropping system. In addition, bean quality studies have been carried out. It has not been possible to establish the link between cocoa quality, production and environmental conditions or cropping systems. This report therefore focuses on the productivity of cocoa cropping systems. The results of a bean quality assessment for Malaysia and Ghana is included in Appendix I.

The report itself has the following purposes:

1. To disseminate simulation results of the CASE2 simulation model.
2. To provide guidance in the interpretation of model output obtained with the CASE2 simulation model, including:
   - an analysis of regional differences in potential for cacao production;
   - an analysis of differences in cacao production in various cropping systems; and
   - an assessment of the importance of agronomic, climatic and plant attributes for cacao production.
3. To set a research agenda for cacao studies leading to an improved understanding and better estimates of cocoa production.
4. To serve as reference for simulations carried out by users of the CASE2 simulation model.

1.2 Guide to the report

The report starts with an introduction to the model (Chapter 2), including some background information on model input and output and on the physiological processes modelled. The remaining chapters all contain results obtained with the model. Chapter 3 contains an example of model output for Malaysia and Ghana. The explanation that is provided with the model output may help to better understand the output presented elsewhere. In Chapter 4 model output is compared to observed values in order to validate the model. Chapter 5 contains results of a sensitivity analysis that identifies those input parameters that have the largest impact on model output in terms of bean yield and biomass growth. Chapter 6 reports on various scenario studies that have been carried out using the model for various regions, cropping systems, soil types, etc.. Chapter 7 identifies issues related to cacao production and yield that need further study.

The appendices contain the results of a bean quality study in Ghana and Malaysia (Appendix I) and a comparison of model output using weather information on a daily or a monthly basis (Appendix II).

2. Description of the model

This chapter provides a brief description of the simulation model CASE2 (“CAcao Simulation Engine” for water-limited production) that has been used to obtain the simulation results presented in this report. Only those aspects of the model that are necessary to understand the model output are explained in this chapter. A more complete description of the model is included in a separate report (user’s manual; Zuidema & Leffelaar 2002). A complete program manual is published separately (model description and technical program manual Zuidema et al., 2002).

2.1 Purpose of the model

CASE2 is the CAcao Simulation Engine for water-limited production. It is a simulation model that produces estimates of the growth and production of cocoa crops depending on physical (weather and soil) conditions, on cropping system (shade trees, plant age) and on plant characteristics (physiology and morphology). Growth and yield estimates produced by CASE2 are calculated using detailed knowledge on the physiology, morphology, light interception, and uptake and loss of water of cacao trees. This knowledge is largely obtained from existing scientific literature on cacao. CASE2 is a generally applicable model, and is not specific to one specific region, cropping system or variety. However, by using weather data as input in the model, location-specific simulation results are obtained.

The CASE2 simulation model serves the following purposes:
1. To estimate cocoa yields in relation to weather and soil conditions and cropping systems;
2. to obtain insight in factors determining production;
3. to integrate existing knowledge on the physiology and morphology of cacao trees; and
4. to identify gaps in knowledge on the physiological basis for estimating cocoa growth and yield.

2.2 Background of the model

The CASE2 model (version 2.2) is partly based on two existing simulation models for agricultural production. Firstly, the skeleton of CASE2 is based on the general crop growth simulation model called SUCROS (Simple and Universal CROp Simulator; van Laar et al. 1997). SUCROS has been used for growth and yield calculations of a number of (mostly annual) crops. In SUCROS, photosynthesis, respiration and growth of plants are simulated in detail. In the version of SUCROS dealing with water-limited production (SUCROS2), water uptake (by the crop) and water loss (due to drainage and transpiration) are also included. This version was used for CASE2.
Secondly, parts of the INTERCOM model (an INTER-plant COMPetition model, Kropff & van Laar, 1993) have been used for the development of CASE2. This model has been developed to simulate competition among crops. As cocoa is often grown under shade trees, part of the total day light is intercepted by shade trees before reaching the cacao trees. Those parts of the INTERCOM model dealing with light interception and photosynthesis were incorporated in CASE2. Furthermore, CASE2 makes use of an existing water balance routine (DRSAHE, van Keulen & Seligman, 1987) and evapotranspiration routine (van Kraalingen & Stol, 1997).

CASE2 also uses the FSE system for crop simulation (van Kraalingen, 1995). This system has the overall control of the simulations, takes care of reading weather and plant data and generates output files.
Several previous versions of CASE2 exist (1.0, 1.1, 2.0, 2.1 and a modification of 2.0). Two of these have been documented (version 1.1 in Gerritsma, 1995, and a modification of version 2.0 by Mommer, 1999). The major changes with versions 2.1 and the modified version 2.0 are in the partitioning of assimilates over different plant parts, in the calculations of leaf production and leaf loss, in the vertical distribution of roots in the soil, on the growth of taproot and lateral roots and on the influence of reduced water availability on tree morphology. Previous versions have been used for growth and yield simulations for two publications (Gerritsma & Wessel 1996, 1999).

2.3 Model limitation

CASE2 is a model, and hence a simplification of reality. Conclusions on the basis of model output should be drawn with care. The quality of the simulation output depends on the knowledge of the processes described in the model and the quality of the input data. Shortcomings in this knowledge is reflected in model output. Although many basic physiological processes are well known for many crops, the specific nature of cacao requires specific knowledge on certain aspects. As such knowledge is not always available, model output should be judged with care.

The following table provides a brief account on the applicability of CASE2. The issues are discussed below. Part of the issues raised is not so much related to the lack of information or knowledge, but to the purpose of the model (see Section 2.1).

What is possible and impossible using CASE2?

	Possible	Not possible
1	- *Simulate* or *estimate* growth and yield - Reveal patterns of growth and yield - Provide insight in cocoa production	*Forecast* growth and production
2	Produce fairly accurate estimates of growth and production for different climatic regions	Produce very precise estimates of growth and production for a specific location or cropping system
3	Produce generally applicable estimates of growth and production	Assess differences in growth and yield of different varieties or cultivars
4	- Estimate potential and water-limited growth and yield - Estimate nutrient loss due to bean harvest	- Estimate nutrient-limited growth and yield - Estimate growth and yield limitation due to pests and diseases
5	Estimate butter hardness of harvested beans	Estimate other quality parameters
6	Estimate periodic leaf and pod development due to seasonal variation in rainfall and temperature	Simulate leaf flushing and fruiting peaks
7		Simulate tree senescence

(1) CASE2 is not meant for yield forecasting. Our limited physiological knowledge of the production system, the uncertainty in the values of input parameters and the general applicability of the model do not allow its use for yield forecasting. Nevertheless, model simulations produce rather accurate estimates of cocoa growth and yield (see Chapter 4 on model validation). Such

estimates may be used to compare regions and cropping systems. Furthermore, the incorporation of the main physiological processes in a detailed way into the model offers the possibility to obtain insight in the cacao production system.

(2) The input parameters for CASE2 have been derived from field studies in very different regions and cropping systems. This implies that CASE2 should not be applied to obtain very precise estimates of growth and yield potential in a certain region and a certain cropping system, but for more general comparisons between regions and cropping systems. As many processes described in the model are "universal" (light interception, photosynthesis, maintenance respiration, etc.), the model is very well suited for such general, large-scale comparisons.

(3) Varieties or cultivars of the cacao tree may differ substantially in morphological and physiological characteristics. This variation is not included in the model, due to the lack of comprehensive sets of information on plant characteristics required. In its present state, most input parameters on plant characteristics are for Amelonado cacao, but information on other varieties is also used (see model description and technical program manual for information on the varieties studied for input parameters, Zuidema et al., 2002).

(4) CASE2 may be used to simulate both potential (that is: not limited by water or nutrient supply, nor by pests and diseases) and water-limited growth and yield of cacao trees. However, the model does not take into account the influence of nutrient limitations or pest and disease incidence. As for nutrients, CASE2 only produces information on the amount of nutrients "leaving" the system due to the harvest of beans.

(5) The quality of cocoa beans is certainly related to the physical circumstances in the plantation. However, not much is known about which of these circumstances determine which aspects of the cocoa quality and how. For butter hardness, an empirical relation with temperature has been found. This relation is used in CASE2 to calculate butter hardness of harvested beans.

(6) Leaf and pod (fruit) growth of cacao is highly periodical: leaves appear in flushes and pod initialisation and growth is periodical as well. As the factors determining leaf flushing are complex and its physiology is not completely understood, this is not included in the model. Periodicity in pod growth is also complex, depending on several factors. Nevertheless, some periodicity in leaf and pod growth is included in the model as a result of seasonal variation in water availability and temperature. Furthermore, as the model is used over long periods of time (years), short-term processes such as leaf flushing need not to be considered, because over long periods average leaf area is of importance for the production of biomass and yield.

(7) With increasing age, cacao trees gradually loose vigour, produce less pods and die off. The physiological basis of this senescence process is poorly known, and there is little empirical information on senescence processes in cacao. Therefore, and because it is not the purpose of the model to address the specific problems in old cacao plantations, senescence has not been included in the model. Growth and yield of model trees is thus not decreased at high age, although in reality this may happen. Also, the lower life span of cacao trees grown without shade, compared to that of shaded trees is not included in the model. To prevent unrealistic simulation results, the maximum age for cacao trees in the model is set to 40 y.

2.4 Validity of the model

Simulations with CASE2 cannot be carried out for all possible climatic conditions or cropping systems. There is a certain "validity space" for which simulations can be carried out. This is determined by (1) physical circumstances that do not allow cacao to grow and (2) certain limitations of model simulations.

The following physical boundaries are defined for the model:

- Altitude: < 1400 m
- Average day temperature: >10 and <40 ºC
- Annual precipitation: > 1250 mm y^{-1}
- Leaf layers of shade trees: < 3 m^2 leaf m^{-2} ground
- Total soil depth: > 1.5 m

No maximum is set to annual precipitation as cacao may be grown at locations with very high rainfall provided that soil characteristics are favourable (Wood & Lass 1985). Total soil depth is important as the taproot of cacao trees should be able to freely penetrate into the soil up to a depth of 1.5 m. Cocoa is usually not grown on shallow soils, for this reason. The number of leaf layers of the shade tree canopy (LAI – leaf area index) is set to a maximum of 3 as higher values would severely limit the possibility of cacao growth (at higher values only 15-25% of the total daylight would be received by the cacao trees).

The following boundaries are based on limitations of the model:

- Planting density: > 700 and <2500 plants ha^{-1}
- Plant age: > 3 and < 40 y
- Plant weight at start of simulation: > 18.5 and < 70 kg dry weight per plant

CASE2 assumes that cacao trees form a closed canopy. When planted at a very low density, or when planting small or young trees, this assumption is not met. A maximum value for the planting density is defined as at high densities, competition between cacao trees affects the growth and yield. The consequences of competition among cacao trees are not modelled in CASE2. A maximum value for cacao size or age is set because in reality cacao trees tend to grow and produce less at high age (or large size); they then gradually senesce and die off. It is thus assumed that at density of <2500 trees ha^{-1}, competition does not (considerably) limit growth and production of individual trees.

2.5 Main model assumptions

Below, the main assumptions of CASE2 are briefly listed. It should be noted that a large number of other – more specific – assumptions are made in the development of the model. A more detailed account of these assumptions will be provided in the technical program manual (Zuidema et al., 2002).

No nutrient shortage
CASE2 assumes that nutrients are not limiting the growth and yield of the simulated cacao plantations. For situations in which simulated yields are high, this probably implies that in reality nutrients should be added to the plantation as nutrient availability will be limiting.

No incidence of pests and diseases
Effects of pests or diseases are not included in CASE2.

Closed and homogeneous canopy, homogeneous shading
CASE2 assumes that the canopies of cacao and shade trees are closed and homogeneous. This implies that the number of leaf layers (leaf area index) of both trees is the same at any location within the modelled plantation.

No senescence
The model assumes that growth and yield of cacao trees is not affected at high age. The physiological processes that result in tree senescence are not included in the model.

No pruning
Pruning of cacao trees is not included in CASE2. No biomass except for ripe pods is artificially removed from the model trees.

2.6 Model input and output

In a simplified form, the model input and output are shown in Figure 2.1. More complete information on input and output parameters and on model structure can be found in the user's manual (Zuidema & Leffelaar 2002) and technical program manual (Zuidema et al., 2002).

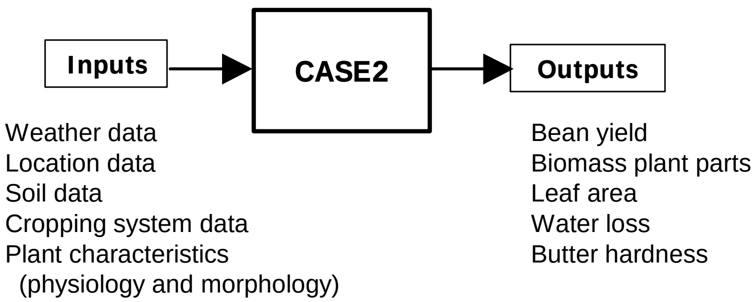


Figure 2.1.
Simplified diagram of inputs and outputs in CASE2. Further explanation is provided in the main text.

Input parameters
Weather data include precipitation, radiation, minimum and maximum temperature, and vapour pressure. Soil data include information on the amount, thickness and physical characteristics of soil layers. Cropping system data include information on planting density, age at the start of the simulation and characteristics of shade trees. Plant characteristics include parameters that are used to calculate rates of photosynthesis, respiration and transpiration; parameters that are used to distribute biomass over plant parts (over leaves, wood, roots and pods); vertical distribution of roots in the soil; ripening and growth of pods; leaf age, etc.
Part of the input parameters for CASE2 are time specific. Weather information (temperatures, rain, radiation and vapour pressure) is specific for one day or for one month. (In the latter case, daily values are generated by the model on the basis of the number of rain days.) Input parameters on plant physiology and morphology, on soil characteristics and on cropping system are not time-specific.

Output parameters
Bean yield is expressed in terms of dry fermented beans. Biomass of plant parts (leaves, wood, taproot, lateral roots and pods) as well as the growth in biomass of plant parts is obtained. Also, leaf area and leaf area index (LAI) of the cacao trees is calculated. Information on water loss through evaporation (from the soil) and transpiration (from the plant) is also obtained. Finally, the butter hardness of the harvested beans and the amount of nutrients lost due to bean harvest are calculated.

Model output can be generated for each simulation day, but also for periods of 10 days or for entire years. In the latter two cases, summed values for parameters such as growth and yield are provided in the output.

2.7 The model cacao tree

For the purpose of the simulations, the cacao tree is divided into "functional parts": leaves, wood, taproot, lateral root and pods (fruits). This division is shown in Figure 2.2 Also included in this figure is the layer of leaves of the shade tree and the soil layers. Below, the characteristics of the different parts of the cacao tree and the shade tree are explained.

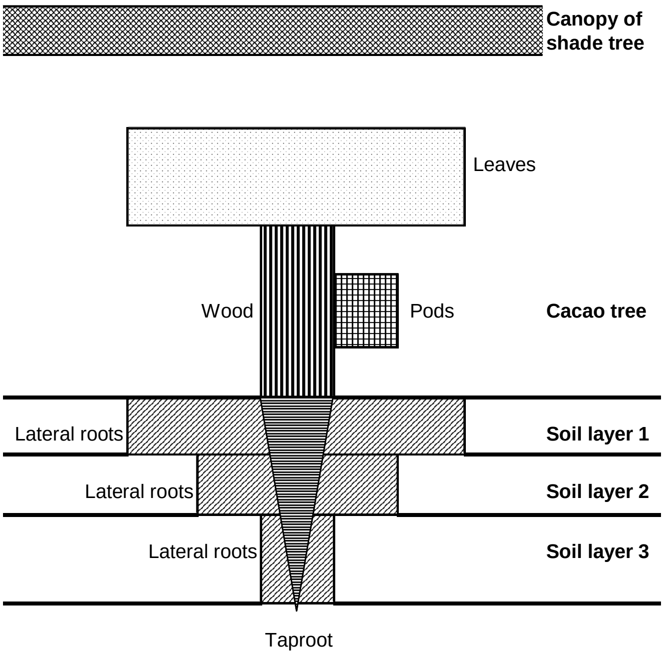


Figure 2.2. Schematic representation of the model cacao tree. The boxes indicate the different plant parts that are distinguished in the model. As the model assumes a homogeneous and closed canopy of cacao trees, the neighbouring model trees border directly to the canopy of the pictured tree. See main text for further explanation.

Shade tree

In CASE2, shade trees are characterised by their canopy only. The shade canopy is characterised by three parameters: the number of leaf layers (LAI – leaf area index), the extinction coefficient of the shade tree (this is the proportion of light intercepted by one layer of leaves) and the lower and upper height of the canopy. The first parameter may depend on the planting density of shade trees and is specific to the type of shade tree used. The second parameter is a characteristic of the shade species. The canopy heights are important to simulate growth and yield for cropping systems in which short shade tree are used, causing the canopies of cacao and shade trees to overlap.

Cacao tree

Leaves. The leaf part in the model is characterised by total leaf weight and leaf area. Leaves have a certain leaf life span and die after having completed this life span. Additional leaf loss occurs in situations of water shortage. New leaves are formed continuously. The leaf area index (LAI – the number of leaf layers of the cacao tree) is another characteristic of the canopy.

Wood. The wood part of the tree is characterised by total wood weight, which includes both the stem and branches of the tree. New wood is formed continuously and wood is lost as litter (fallen branches).

Pods. The pods (fruits) of the model tree are characterised by their weight and development stage (ripening stage). All pods in the model are divided into age categories: pods of 1, 2, 3, etc days are

treated separately in the model. Apart from their age, pods in a category are characterised by a certain weight and a certain development stage. When the development stage of a certain category reaches the mature stage, pods in that category are added to the harvest.
Taproot. The taproot of the model tree has a certain weight and a certain length. The length of the taproot is determined on the basis of its weight (assuming that the taproot has the shape of a cone, with a certain relation of length and diameter, and a certain wood density).
Lateral roots. The lateral roots are divided into two parts: roots that may take up water (with a diameter of <2 mm) and coarse roots. Both water-absorbing and coarse roots are characterised by their weight, and both are continuously renewed; that is: part of the roots dies off each day and this part is replaced by new roots. Water-absorbing roots are distributed over the different soil layers following an exponential decline of root density with increasing depth (in Figure 2.2 this is shown for all lateral roots). These roots are distributed up to the depth reached by the tip of the taproot. Length and surface area of the water-absorbing roots are derived from their weight, specific length and diameter.

2.8 Processes in the model

This section provides some explanation on the simulation processes in CASE2 that convert model input into model output. Before explaining the processes in the CASE2 model, it is necessary to obtain an idea on the simulation procedures followed in CASE2 (Section 2.8.1). Subsequently, three processes dealing with the conversion from solar radiation to cocoa beans are discussed (Sections 2.8.2-2.8.4) followed by two processes related to water uptake and loss.

2.8.1 Simulation procedure

Simulations in CASE2 are carried out following fixed sequence of calculations (see Van Kraalingen 1995). The time step for the calculations is one day. This procedure is visualised in Figure 2.3.
The simulation procedure starts with cacao trees of a certain size or age. Based on this information, other initial plant characteristics such as leaf area, root distribution and biomass of the different plant parts are determined. The initial tree characteristics (*states*) and the growing conditions (cropping system, weather conditions and soil characteristics) are then used to calculate rates of photosynthesis, respiration, water uptake, water loss, etc.. These rates are used to determine the growth in biomass. Then, the values of these states are updated by adding their growth rates integrated over one day to obtain the values for the next day. During this next simulation day, the new states are used to calculate new rates, which then are used to obtain the state values for the following day, etc. This iterative procedure continues until the final simulation time, which is specified by the user.

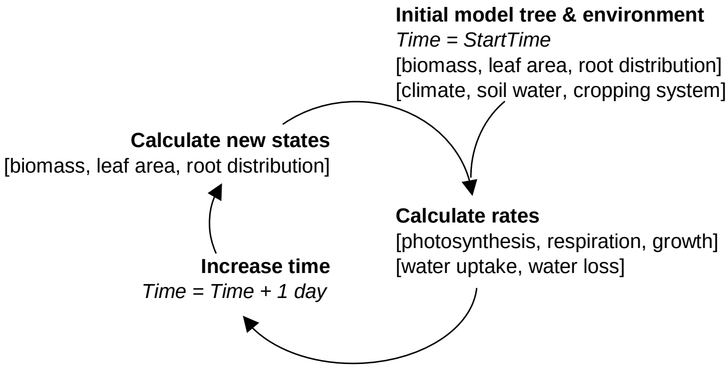


Figure 2.3. Representation of the simulation procedure followed in CASE2. The arrows denote the sequence of calculations in the model. This sequence of procedures is applied in many related models (e.g. SUCROS). See main text for further explanation. Based on van Kraalingen 1995.

2.8.2 From radiation to photosynthesis

In CASE2, solar radiation is used to calculate the rate of photosynthesis of the cacao trees (see Goudriaan & van Laar 1994, Kropff & van Laar 1993). Figure 2.4 shows the different steps in CASE2 that “transform” solar radiation to photosynthesis. Total daily solar radiation is one of the weather inputs in CASE2. Part (around 50%) of this total solar radiation is photosynthetically active radiation (PAR) that can be used by plants. The total amount of PAR is first intercepted by the shade trees. Part of this radiation is absorbed by the shade trees and part is transmitted by the shade tree canopy and may be absorbed by the cacao trees. The amount of radiation transmitted by the shade trees depends on the number of leaf layers (LAI) in the shade tree canopy and on the proportion of light intercepted by one layer of leaves (the extinction coefficient). In CASE2, shade trees do not evenly reduce the available radiation. That is, patches of direct light are transmitted through the canopy. Cacao trees thus receive both direct and indirect light.

As for the shade trees, the amount of light intercepted by the cacao trees depends on the number of leaf layers and the extinction coefficient of the cacao trees. Part of the intercepted light is absorbed and may be used for photosynthesis. Part of the intercepted light is direct radiation and part is indirect light. The amount and fraction of direct and indirect radiation that reach the cacao canopy is determined by assuming a certain (spherical) distribution of leaf angles and by knowing the position of the sun at each moment of the day.

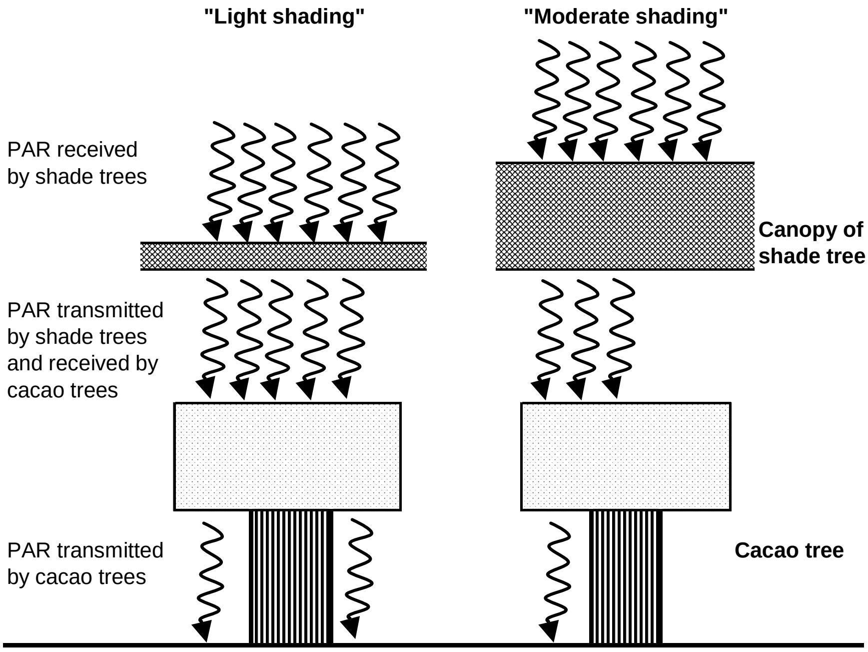


Figure 2.4. Schematic representation of light interception by shade trees and cacao trees, as used in CASE2. Arrows represent solar radiation (PAR = photosynthetically active radiation). The amount of radiation intercepted and absorbed by the shade tree canopy depends (among other things) on the number of leaf layers (leaf area index). The left part of the drawing shows the situation for light shading, in which a large part of incoming radiation is transmitted through the shade tree canopy. The right part shows the situation for moderate shading, in which only half of the incoming radiation reaches the cacao tree. See main text for further explanation.

The rate of photosynthesis depends on the amount of light absorbed by the cacao trees. Apart from this, it also depends on the temperature (with lower photosynthesis at very high and very low temperatures) and water availability (with lower photosynthesis at low water availability).

2.8.3 From photosynthesis to growth

In CASE2, the assimilates (carbohydrates or sugars) produced by photosynthesis during the day are used for three purposes. This is illustrated in Figure 2.5. First, assimilates are used for *maintenance respiration*. This covers all costs for biochemical processes at cellular level, transport costs within the plant, etc.. If there are still assimilates left, these are used for *replacement* of plant parts. This involves the replacement of those plant parts that are lost during that day as a result of turnover (fallen leaves, dead roots, fallen branches and harvested fruits). If after this replacement there are still reserves left, these are used for *net growth* of plant parts. Thus, the model uses a fixed order of assimilate use. This implies that a good functioning of the plant's physiology (*maintenance respiration*) has priority over maintaining the size of the plant (*replacement*), and that the latter has priority over the net growth of the plant (*net growth*).

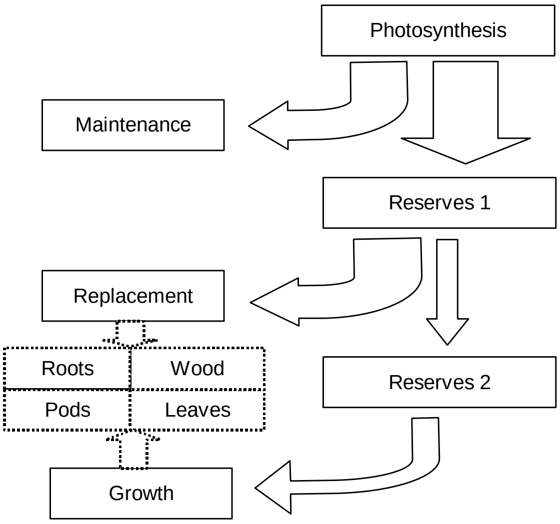


Figure 2.5. Flow diagram showing the sequence of assimilate use as modelled in CASE2. Boxes with full borders denote amounts of carbohydrates; boxes with dotted borders denote amounts of biomass. Arrows with full borders denote fluxes of carbohydrates; arrows with dotted borders denote conversions from carbohydrates to biomass. See main text for further explanation.

2.8.4 From growth to dry beans

Part of the available reserves is used for the growth of fruits (pods) of the model trees (see Figure 2.6). The amount of reserves invested in pods depends on the total amount of available reserves, on the amount of harvested pods (the biomass "lost" when pods is replaced) and on the increase in pod weight with increasing total tree weight. Pods develop to maturity during a certain period of time; the length of this period depends on the temperature (at high temperatures, pod development is faster). Pods are "harvested" in the model when they are mature. The weight of harvested pods is then used to calculate the weight of dry, fermented beans, using information on the fraction of beans per pod, the moisture content of beans and the loss of weight during fermentation. A known (empirical) relation between temperature at the onset of fruit ripening and the ratio of saturated and unsaturated fatty acids is used to determine the butter hardness of the harvested beans.

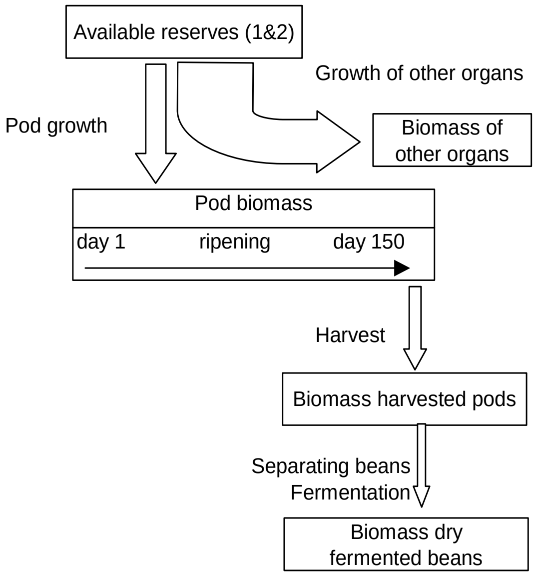


Figure 2.6. Flow diagram showing the sequence of procedures to obtain dry fermented beans from a certain amount of available reserves, as modelled in CASE2. Boxes denote amounts of carbohydrates or biomass. Arrows denote fluxes of carbohydrates or biomass. The arrow within the Pod biomass box represents the ripening of pods. In this graph pods of 150 days are taken to be ready for harvest, but this may vary depending on the temperature. See main text for further explanation.

2.8.5 From rain to water uptake

Rainfall enters the model system at each simulation day (this information is derived from the weather data). Rain is intercepted by the canopies of shade trees and cacao trees, and may reach the soil by falling through the canopy (Figure 2.7). Depending on the amount of rain, part of the rain does not reach the soil, but evaporates from the leaf surface. Water movement and content in the soil is described in a water balance model (see van Keulen 1975, Driessen 1986). The amount of rain reaching the soil enters the first soil layer (infiltration). In the soil water moves downward; upward capillary movement is assumed to be negligible (Figure 2.7). When the amount of water in a soil layer has reached a certain value (“field capacity”), the surplus is transported to the next (lower) layer. In case this layer is already “filled”, the water moves to the next layer, etc. The maximum amount of water that can be retained in a soil layer depends on the type of soil (soil texture) and the thickness of the soil layer. When all layers are filled and there is still excess water, this is drained externally to below the lowest soil layer and is lost.

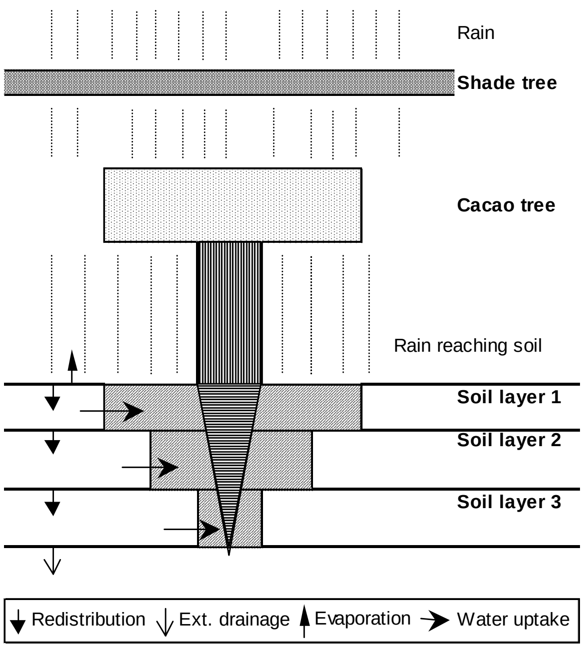


Figure 2.7. Schematic representation of the interception of rain and the transport of water in the soil, as modelled in CASE2. Incoming rain is first intercepted by the canopies of shade and cacao trees. Part of it reaches the soil via through fall. Transport among soil layers is by downward movement (redistribution). Water is lost by evaporation and external drainage. Water uptake takes place in soil layers where fine roots are available. See main text for further explanation.

The uptake of water from a certain soil layer depends on three parameters: (1) the amount of water available in the layer, (2) the total surface of fine cacao roots (<2 mm in diameter) in the layer and (3) the amount of water lost due to transpiration of water from the leaves. The first factor (amount of available water) is a resultant of input of rain, the transport of water between soil layers and the water-holding capacity of the particular soil layer. The second factor (root surface) depends on the weight of fine roots and on the amount of root surface per unit weight. The weight of fine roots in a certain soil layer, in turn, depends on the total fine root weight in the soil and their vertical distribution, which is based on a steep decline of fine root density with increasing depth. The third factor (water loss through transpiration) depends on the amount of radiation intercepted by the canopy, the temperature, the vapour pressure and on the difficulty (resistance) with which water transpires from cacao leaves (see next Section on water loss).

2.8.6 From energy balance to water loss (evapotranspiration)

The loss of water from leaves of the cacao tree depends on the energy balance of the tree (see Van Kraalingen & Stol 1997; Mommer 1999). The energy from intercepted radiation is an input of this balance, and the heat loss through the soil, through the air and through transpiration are the energy outputs. Depending on the amount of radiation and the air temperature, more or less transpiration is required to maintain the energy input and output at balance and prevent the temperature in the plant from becoming too high.

2.9 Parameterisation of the model

The values for all input parameters in CASE2 are taken from publications on the cultivation, physiology and morphology of the cacao tree. No field studies were carried out to collect information used in the model. In spite of the large quantity of publications on cacao, for several of the model's input parameters only rough estimates could be obtained, and in some cases no values were available. In the latter case, a best guess was used and the model was tested using this value. The sources of all input parameters used in CASE2 are documented in both the user's manual (Zuidema & Leffelaar 2002) and the technical program manual (Zuidema et al., 2002).

3. Detailed example of model output

3.1 Purpose

The purpose of this Chapter is to show the possible output of CASE2 and to provide some guidance in its interpretation. The figures presented in this Chapter are obtained using the default values for all input parameters. In case output values for new runs deviate from those presented here, this indicates that input parameters were chosen differently from the default values.

3.2 Approach

The simulations of which results are presented in this Chapter were carried out using the default set of input parameters provided with the model (a list with these values is included in the user's manual, Zuidema & Leffelaar 2002). The input parameters that may be changed by the user (within the boundary values presented in Section 2.4) were set to the following values (abbreviations between parentheses refer to the variable name in the program):

Planting density (NPL):	1000 trees ha^{-1}
Initial tree age (AGEIYR):	4.11 year
Cacao lower height of canopy (HGHL):	0.75 m
Cacao upper height of canopy (HGHT):	3.5 m
Shade tree leaf area index (SLAI):	0.2 ha ha^{-1}
Shade tree extinction coefficient (SKDFL):	0.6
Shade tree lower height of canopy (SHGHL):	4 m
Shade tree upper height of canopy (SHGHT):	10 m

Simulations were carried out for two locations: Malaysia (Tawau, Sabah) for 1983-1993, and Ghana (Tafo) for 1987-1997. Climate diagrams for these locations are shown in Figure 3.1. Monthly weather data were used for both site: these data consist of the total rain per month, the number of rain days per month, and the monthly averages for radiation, minimum and maximum temperature

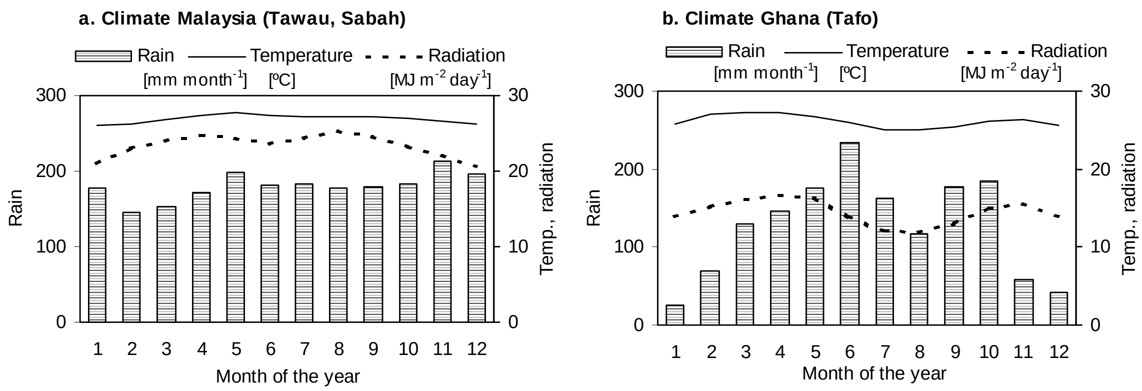


Figure 3.1. Climatic diagrams of the two locations for which example simulation results are presented in this Chapter. Both diagrams are based on monthly weather data. For Malaysia, weather information for 1951-1993 was used; for Ghana the period 1963-1997 was used.

and vapour pressure. For Malaysia temperature data were long-term average values that did not differ between years. Soil characteristics used for the simulations are provided in Table 3.1. As no information on soil type was available for Ghana, only one soil type was used. This also facilitates the comparison of model output between locations.

Output of the example simulations is generated for 10 day-periods and for years. Output per 10 days is shown to provide an idea of the fluctuations in an output parameter over short periods of time, and output per year to show long-term trends. The program variable names of the output as used in CASE2 are mentioned in the figure captions.
Example output is first presented for essential output parameters related to yield, and then for the other – more basic – parameters such as photosynthesis and maintenance respiration.

Table 3.1. Soil characteristics used for example simulations of CASE2. Only physical characteristics related to water content are used, as nutrient cycles are not included in the model. The zoning of the soil is based on cocoa soils in Nigeria (Wessel 1971). Texture classes are based on the sand-silt-clay triangle (Driessen 1986; numbers between parentheses refer to the Driessen soil types). Water content at field capacity (pF=2.0) and wilting point (pF=4.2) are calculated using the water retention curve (Driessen 1986). Program variable names: depth of layer (TKL); texture class (TYL).

Layer	Depth of layer [cm]	Texture class	Water content at field capacity [$cm^3\ cm^{-3}$]	Water content at wilting point [$cm^3\ cm^{-3}$]
1	10	Silt loam (12)	0.359	0.108
2	30	Sandy loam (9)	0.273	0.044
3	30	Loamy fine sand (8)	0.233	0.027
4	150	Loamy fine sand (8)	0.233	0.027

3.3 Yield

Cocoa yield can be expressed as pod yield and bean yield. Although both parameters are calculated in CASE2, no results of the former are presented here as they are not commonly used. Bean yield per 10-day period shows moderately large to large variation in time for both Malaysia and Ghana (Figure 3.2). Variation for Malaysia corresponds rather well to temporal variation in radiation; whereas the large variation found for Ghana can be attributed to the large variation in rain fall there. Important dips in yield for Ghana correspond to extended periods with very low rainfall, in which only a small amount of assimilates is invested in pods. The long-term patterns of bean yield,

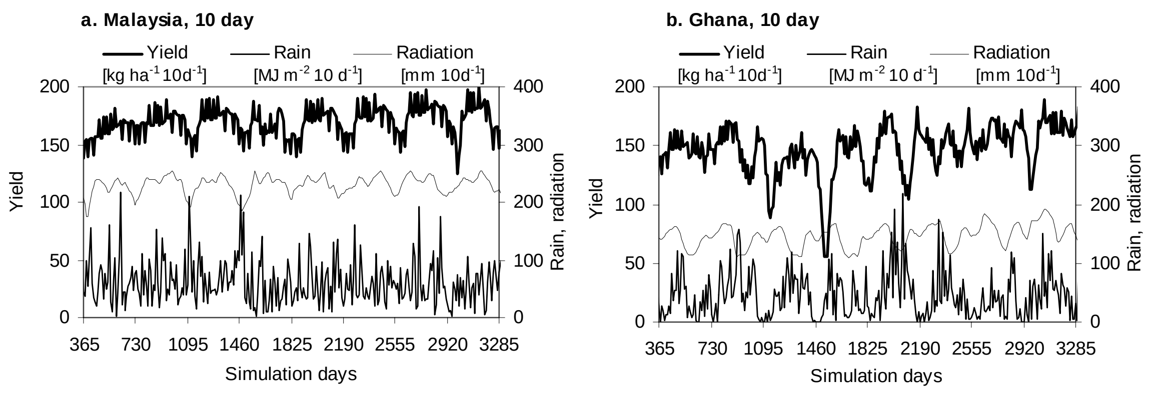


Figure 3.2. Example simulation output for bean yield, compared with rain and radiation, for Malaysia (a) and Ghana (b). Simulation results for 10-day periods are shown for years 2-9 of the simulations. Program variable names: Yield=D10YLDBN; Radiation=D10RDD; Rain=D10RAIN.

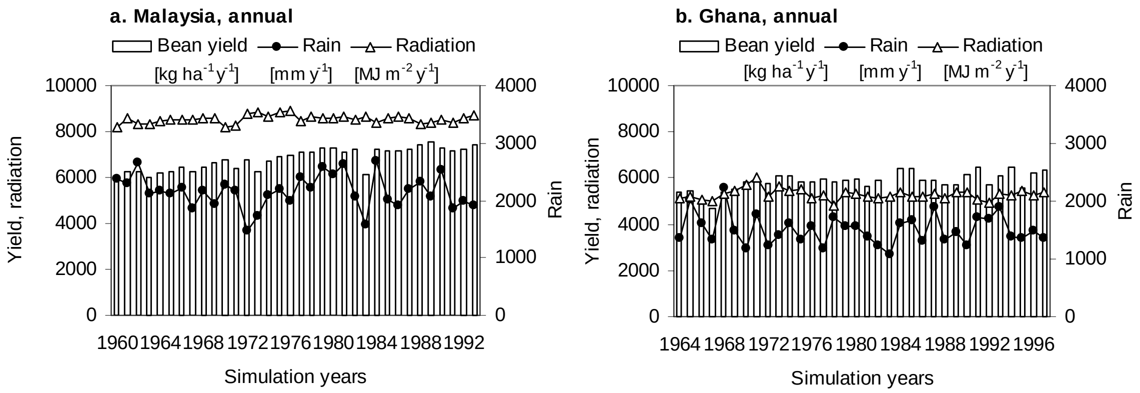


Figure 3.3. Example simulation output for bean yield, compared with rain and radiation, for Malaysia (a) and Ghana (b). Total annual values are shown for years 2-35 of the simulations. Program variable names: Yield = YYLDBN; Radiation = YRDD; Rain = YRAIN.

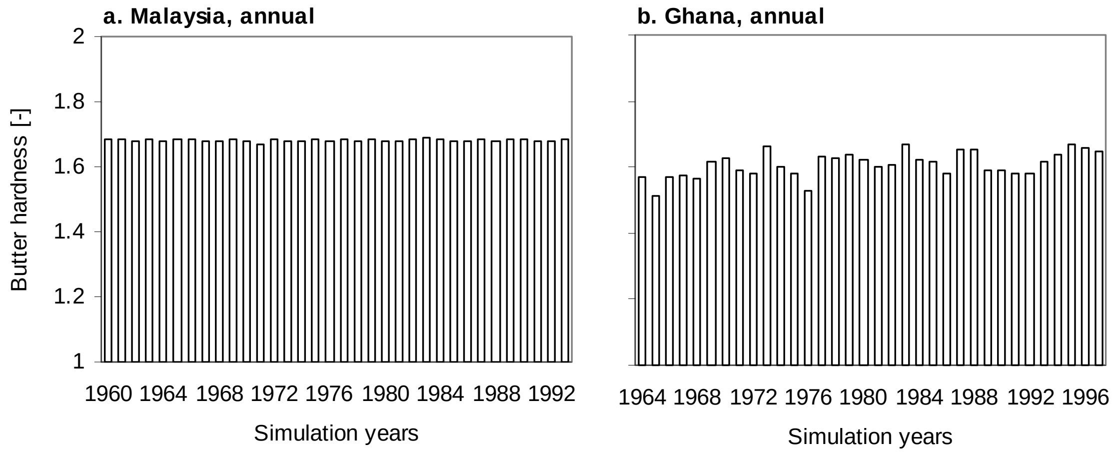


Figure 3.5. Example simulation output for butter hardness of harvested beans for Malaysia (a) and Ghana (b). Total annual values are shown for years 2-35 of the simulations. Note that the lack of variation in butter hardness for Malaysia is caused by the use of long-term average temperature values, and does not necessarily reflect low variation in butter hardness in reality. Program variable names: Butter hardness = YMNBH.

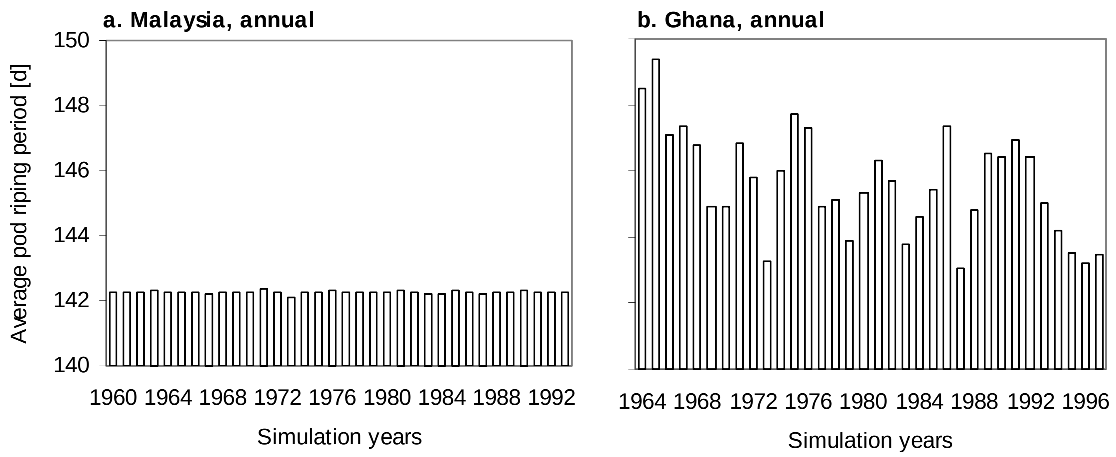


Figure 3.6. Example simulation output for the average ripening period of harvested beans for Malaysia (a) and Ghana (b). Total annual values are shown for years 2-35 of the simulations. Note that the lack of variation in ripening period for Malaysia is caused by the use of long-term average temperature values, and does not necessarily reflect low variation in this parameter in reality. Program variable names: Pod ripening period = YMNIPOD.

radiation and rain (Figure 3.3) show clearly higher annual yields for Malaysia compared to Ghana. This can be attributed to the higher levels of radiation and rain fall in Malaysia. The variation in bean yield between years is moderate and comparable between the two locations. It is difficult to link the variation in yield to variation in rain or radiation: there is no strong correlation between radiation or rain on the one hand and bean yield on the other. Especially in the case of Ghana, the distribution of rain during the year is of importance for bean yield: long periods with little precipitation have a strong negative impact on pod growth (see Figure 3.2).

Butter hardness, the ratio between saturated and unsaturated fatty acids (Wood & Lass 1985) of harvested cocoa beans determines the melting point of cacao butter. It is related to the ambient temperature at the onset of fruit ripening (high temperatures leads to high butter hardness values). Figure 3.4 shows how temporal variation in temperature causes variation in butter hardness. As butter hardness depends on the temperature at fruit setting, there is a time lag of 140-150 days in the correlation between temperature and butter hardness. That is, the butter hardness of harvested beans at a certain time is related to the temperature 140-150 days before that date. Annual averages for butter hardness are shown in Figure 3.5. For both Figure 3.4 and 3.5 is should be noted that the lack of between-year variation for Malaysia is due to a lack of data: long-term average values were used for temperature instead of specific values for each year.
Pod ripening also depends on the ambient temperature. Figure 3.6 shows the annual average value for pod ripening. As for the previous figures, the lack variation for Malaysia is due to the use of long-term average temperature values. For Ghana, some variation exists but all values are within a small range of 143-149 days.

The harvest index (H.I.) is calculated as the ratio between the dry weights of the harvested plant parts and that of the total plant aboveground. For cocoa, the amount of beans harvested per year has been taken as the “harvested part” to calculate H.I.. An index value specific for tree crops has been proposed by Cannell 1985. This harvest increment (H.Incr.) is defined as the (increment in the dry weight of the harvested parts) / (increment in total aboveground dry weight). In CASE2 this is calculated as (dry weight of annual yield) / (annual total aboveground dry weight production). Figure 3.7 shows both index values. The H.I. value gradually decreases in time, probably due to a larger increase in total tree biomass compared to the increase in yield. The value of H.Incr. remains rather constant over time. Between-year variation in both indices is higher for Ghana than for Malaysia, due to higher variation in yield in Ghana.

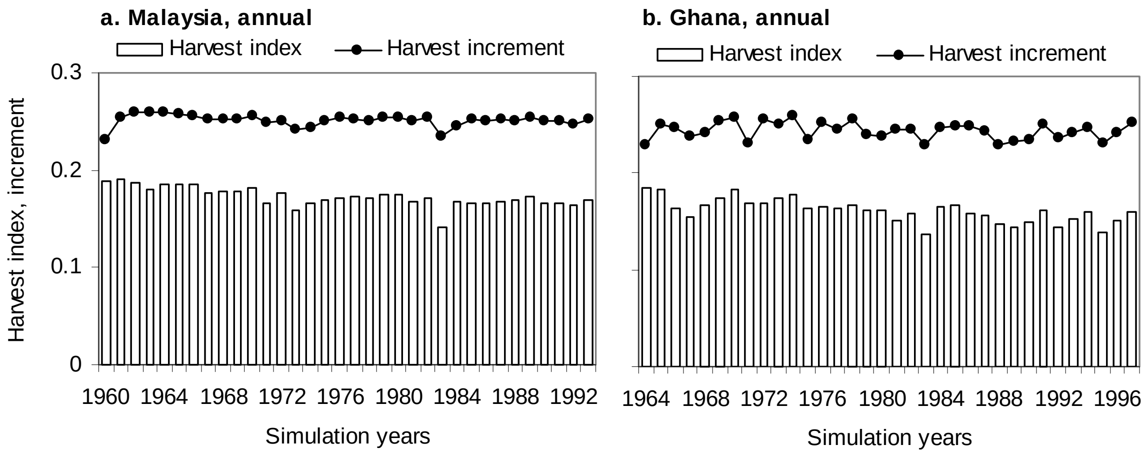


Figure 3.7. Example simulation output for harvest index and harvest increment for Malaysia (a) and Ghana (b). Total annual values are shown for years 2-35 of the simulations. See text for explanation of the parameters. Program variable names: Harvest index = YHI; Harvest increment = YHINCR.

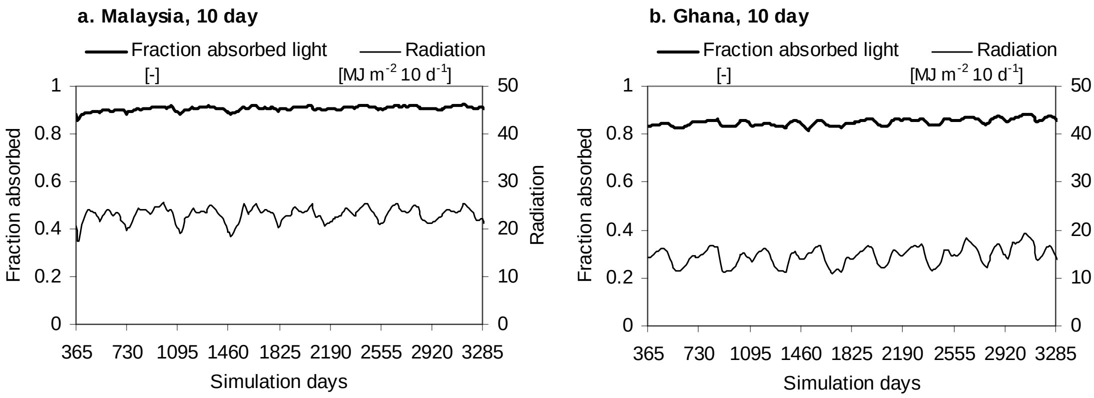


Figure 3.8. Example simulation output for the fraction of light absorbed by cacao trees compared to total radiation, for Malaysia (a) and Ghana (b). Simulation results for 10-day periods are shown for years 2-9 of the simulations. Program variable names: Fraction absorbed = FRABS(1); Radiation=D10RDD.

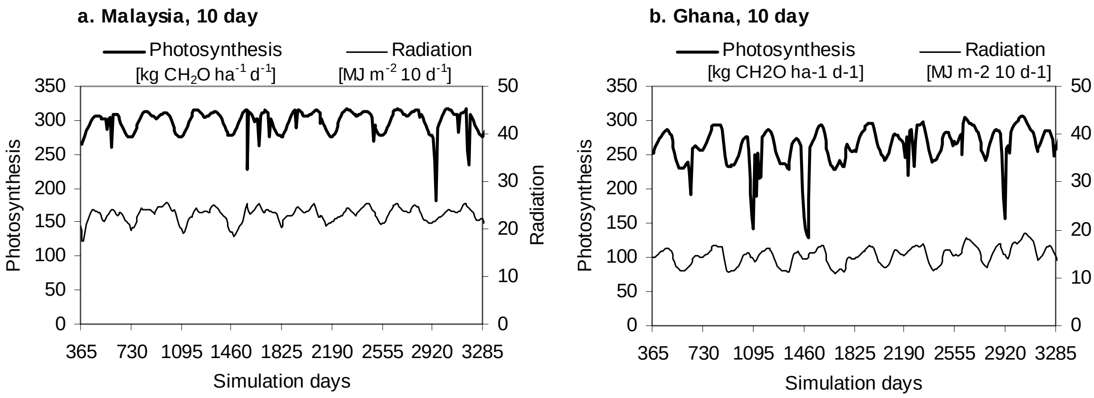


Figure 3.9. Example simulation output for the total (gross) rate of photosynthesis, compared to total radiation, for Malaysia (a) and Ghana (b). Simulation results for 10-day periods are shown for years 2-9 of the simulations. Program variable names: Photosynthesis = GPHOT; Radiation=D10RDD.

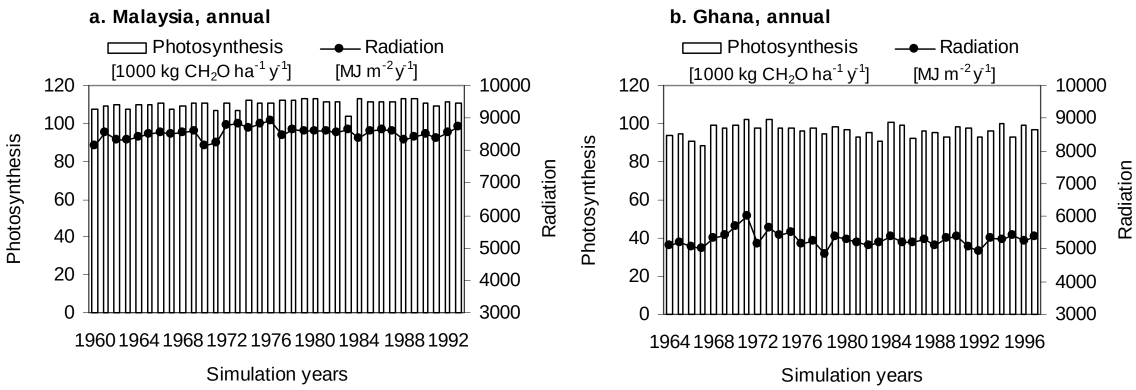


Figure 3.10. Example simulation output for the amount of (gross) photosynthesis, compared to the amount of radiation, for Malaysia (a) and Ghana (b). Total annual values are shown for years 2-35 of the simulations. Program variable names: Photosynthesis = YGPHOT; Radiation = YRDD.

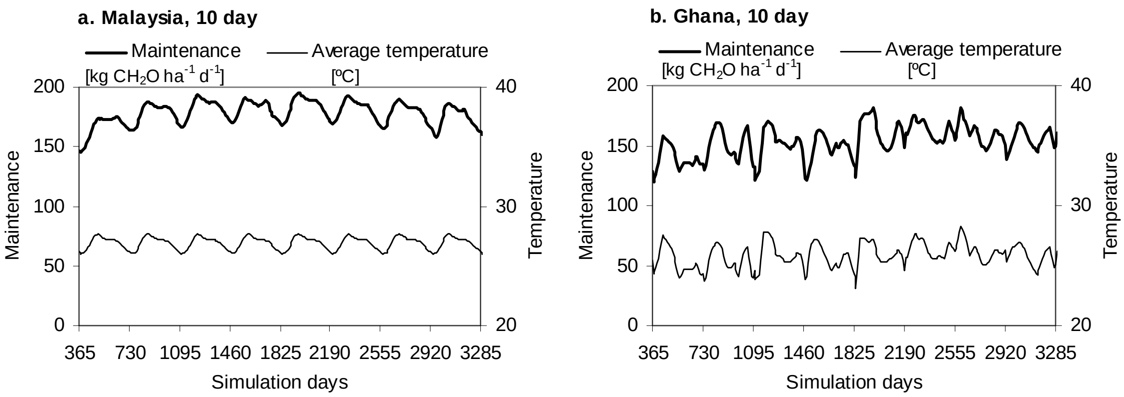


Figure 3.11. Example simulation output for the maintenance respiration compared to average temperature, for Malaysia (a) and Ghana (b). Simulation results for 10-day periods are shown for years 2-9 of the simulations. Note that the reason for the low variation and fixed pattern of temperature in Malaysia is caused by the use of long-term average values. Program variable names: Maintenance = MAINT; Temperature = TMAV.

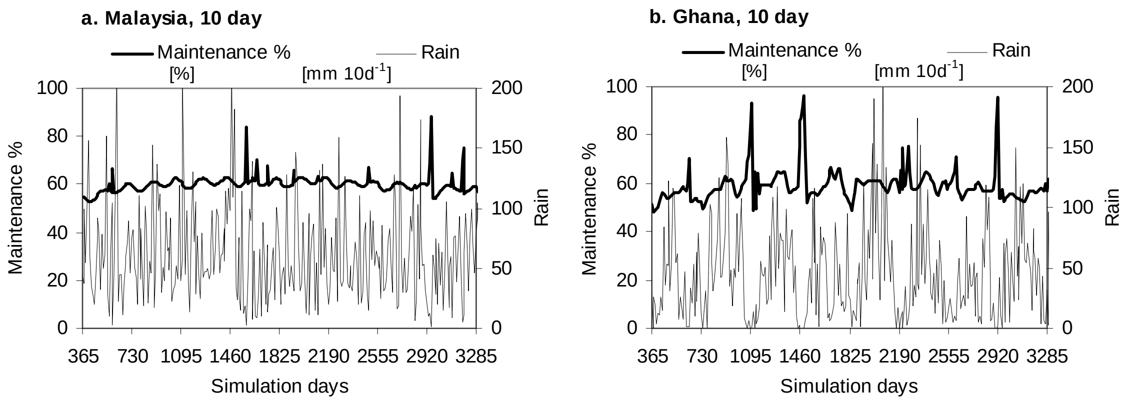


Figure 3.12. Example simulation output for the percentage of total (gross) photosynthesis that is used for maintenance respiration, compared to rain, for Malaysia (a) and Ghana (b). Simulation results for 10-day periods are shown for years 2-9 of the simulations. Program variable names: Maintenance% (calculated as)= MAINT/GPHOT * 100%; Rain=D10RAIN.

3.4 Photosynthesis and maintenance respiration

Part of the total radiation reaching the model cacao plantation is absorbed by the canopy of the shade trees. For the example simulations carried out for this Chapter, ca. 90% of the total radiation is transmitted by the shade trees and can thus be intercepted and used by cacao trees. Figure 3.8 shows the fraction of total radiation absorbed by cacao trees for Malaysia and Ghana. The values for Malaysia are somewhat higher, partly due to the fact that for Malaysia the model trees are larger, having a larger leaf area to intercept light.
The rate of photosynthesis is strongly related to the amount of radiation, as can be seen in Figure 3.9. The sharp dips in these graphs, especially for Ghana are caused by a reduction of gross photosynthesis due to limited water availability (the closure of stomata in the leaves during periods of low water availability is included in the model as a reduction in the gross photosynthesis). Figure 3.10 shows the relation between radiation and photosynthesis over a long period. For Ghana, there is a rather strong relation between annual photosynthesis and annual radiation. That is, around 40% of the variation in photosynthesis can be explained by variation in radiation. For Malaysia there is no correlation at all. The reason for this is the difference in the level of radiation between the two locations. For the Malaysian location, radiation is often at such a high level, that an increase in radiation hardly results in an increase in photosynthesis. That is, the maximum

photosynthesis level A_{max} – the plateau in the light-response curve – has been reached. In Ghana, the light level at which photosynthesis has reached its maximum is usually not yet attained. Maintenance respiration is strongly related to temperature. The correlation of these two parameters is clearly shown in Figure 3.11. An increase in temperature of 10 degrees (above the reference temperature of 25ºC), leads to a doubling of maintenance respiration. When expressed as a percentage of photosynthesis (Figure 3.12), it appears that maintenance respiration uses 55% of the total available assimilates. This value fluctuates due to variation in radiation, temperature and water availability. The strong peaks in the percentage maintenance respiration (especially for Ghana) correspond to periods of low water availability during which photosynthesis is reduced.

3.5 Growth of tree components

In CASE2, growth of plant organs is split into two components: the turnover of lost plant parts and the net growth of plant parts (see Section 2.8.3 for explanation and Figure 2.5). For large trees, the amount of biomass lost per day due to turnover of leaves, roots, pods and wood may be very large. Figure 3.13 shows that the percentage of available reserves used for replacement is high. This amount of available reserves is calculated as the amount of carbohydrates produced by photosynthesis minus the amount of carbohydrates used for maintenance respiration. On average (over 35 years), 93 and 88% of these reserves are used for replacement, for Malaysia and Ghana respectively.

After covering the costs for replacement, the reserves still available are partitioned over different plant parts using newly derived relations between dry weights of the entire tree and that of its organs. As a result, the distribution of biomass over plant parts is rather stable over time (Figure 3.14). Fluctuations in this distribution are caused by periods of low water availability, when leaf production is decreased and leaf fall and root growth are increased. Over longer time periods, variation is small, as can be seen in Figure 3.15.

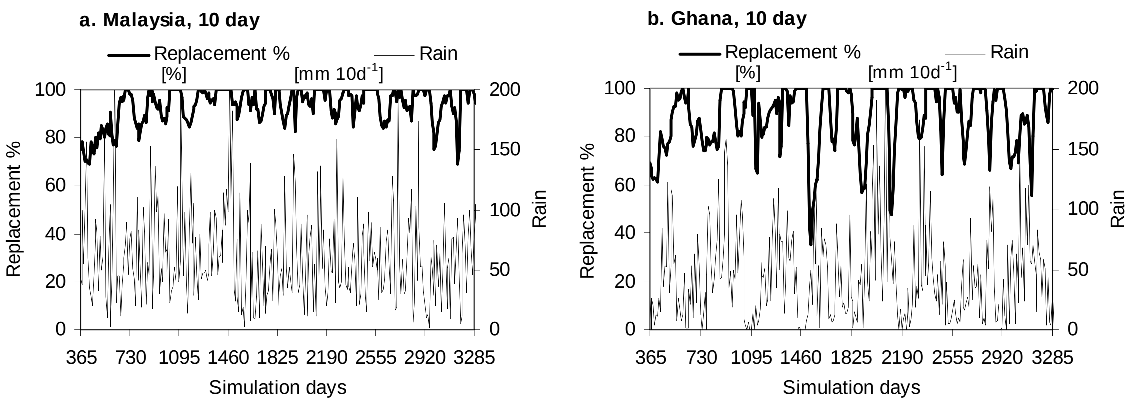


Figure 3.13. Example simulation output for the percentage of available reserves that is used for the replacement of “turned-over” plant parts, compared to rain, for Malaysia (a) and Ghana (b). The available reserves are calculated as the amount of photosynthetic assimilates that is left after subtracting assimilates used for maintenance respiration. “Turned-over” plant parts are leaves, branches, roots or pods that are “lost” during one simulation day, due to turn-over. Simulation results for 10-day periods are shown for years 2-9 of the simulations. Program variable names: Replacement% (calculated as)= GTOT1/GTOT * 100%; Rain=D10RAIN.

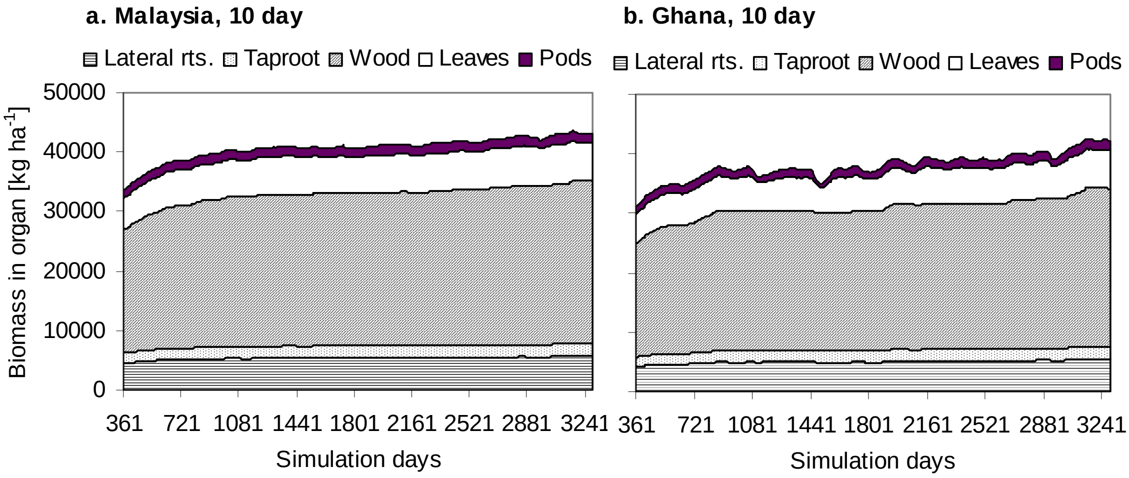


Figure 3.14. Example simulation output for the distribution of biomass over different plant parts for Malaysia (a) and Ghana (b). Simulation results for 10-day periods are shown for years 2-9 of the simulations. Program variable names: Lateral root biomass = WLRT; Taproot biomass = WTRT; Wood biomass = WWD; Leaf biomass = WLV; Pod biomass = WPD.

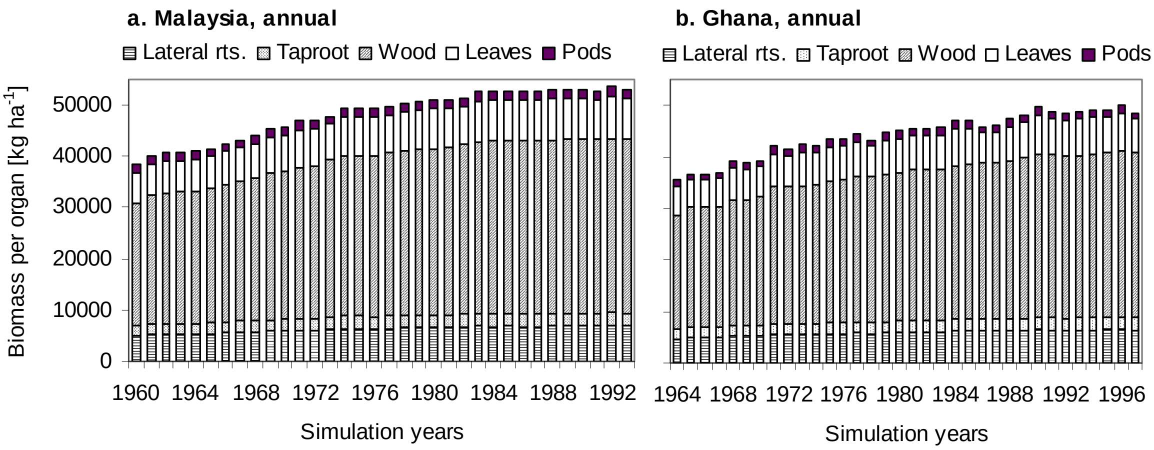


Figure 3.15. Example simulation output for the distribution of biomass over plant parts, for Malaysia (a) and Ghana (b). Total annual values are shown for years 2-35 of the simulations. Program variable names as in Figure 3.14.

3.6 Leaf dynamics

Leaf production and leaf loss strongly depend on rainfall. Figure 3.16 shows strong fluctuations in leaf production, with especially low values for Ghana during long dry periods. The lower leaf production and higher leaf loss during periods of low water availability, lead to lower values of the leaf area index (LAI, the number of leaf layers in the canopy). The pattern in this parameter is shown in Figure 3.17. At the scale of year, the average LAI fluctuates less and without a clear relation with the total annual rain fall (Figure 3.18).

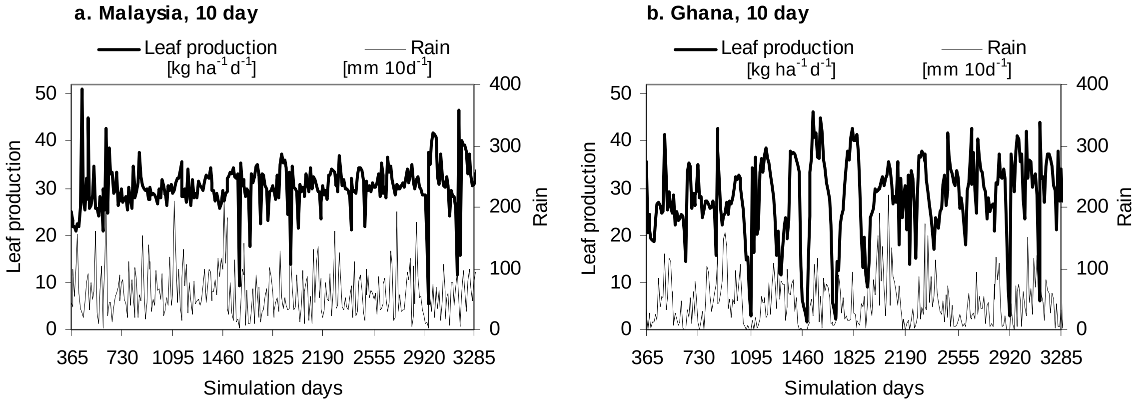


Figure 3.16. Example simulation output for the production of leaves, compared to rain fall, for Malaysia (a) and Ghana (b). Simulation results for 10-day periods are shown for years 2-9 of the simulations. Program variable names: Leaf production = GLV; Rain = D10RAIN.

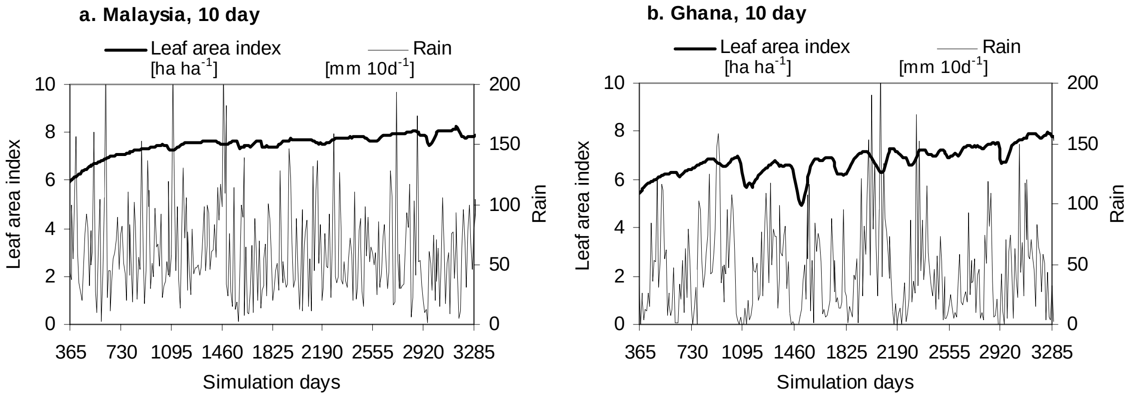


Figure 3.17. Example simulation output for the leaf area index (LAI), compared to rain fall, for Malaysia (a) and Ghana (b). The leaf are index is the number of leaf layers in the plant canopy. Simulation results for 10-day periods are shown for years 2-9 of the simulations. Program variable names: Leaf area index = LAI(1); Rain=D10RAIN.

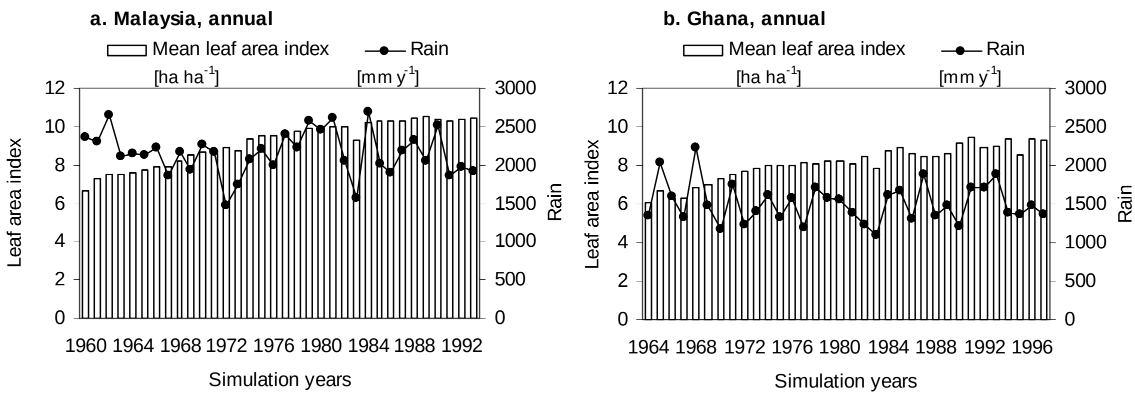


Figure 3.18. Example simulation output for the leaf area index (LAI) compared to rain fall, for Malaysia (a) and Ghana (b). The leaf area index is the number of leaf layers in the plant canopy. Total annual values are shown for years 2-35 of the simulations. Program variable names: Leaf area index = YMNLAI; Rain = YRAIN.

3.7 Root development

The taproot and lateral roots of the cacao tree are treated separately in the model. Part of the lateral roots, the fine roots of < 2mm diameter that can extract water, are distributed over the different soil layers. The depth up to which fine roots are present depends on the length of the taproot. This, in turn, depends on the weight of the taproot. For the example simulations, taproot length increased from 0.91-1.18 m for Malaysia and 0.91-1.16 m for Ghana, both during the period of 2-35 simulation years (age 5-38 years).
Fine roots are distributed over soil layers based on a strongly declining root density with increasing depth. The development of the weight of fine root in each of the four soil layers is presented in Figure 3.19.

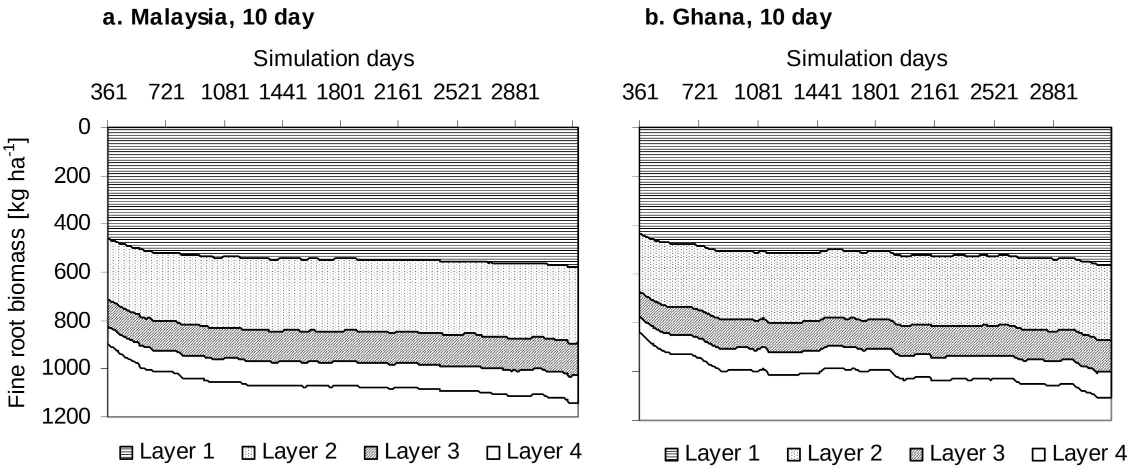


Figure 3.19. Example simulation output for the distribution of fine (water-uptaking) root biomass over four soil layers, for Malaysia (a) and Ghana (b). Characteristics of the soil layers are provided in Table 3.1. Simulation results for 10-day periods are shown for years 2-5 of the simulations. Program variable names: Fine root biomass layer x = WWURT(x).

3.8 Water uptake and loss

The water content in each of the soil layers is simulated in CASE2. The simulation results for the first (upper) soil layer are shown in Figure 3.20, together with the amount of rain. Sharp dips in water content appear during long periods with little precipitation. There are no upward peaks, because water entering a soil layer that is "full" (filled up to field capacity) is directly transported to the next (lower) layer. Simulation results for water uptake from this upper soil layer are presented in Figure 3.21. The large fluctuations in water uptake are due to fluctuations in radiation (high radiation increases transpiration and thus water uptake) and to fluctuations in water availability (when there is no water available, no water can be extracted from the soil layer). The large difference in average water uptake between Malaysia and Ghana is due to the difference in radiation and rain fall (both being higher in Malaysia). As approximately 50% of the fine roots is present in the first soil layer, half of the water is extracted from this layer, as shown in Figure 3.22. The total water loss due to evapotranspiration is shown in Figure 3.23. Again, the amount of radiation and the availability of water largely determine the strong variation in water loss. Over long periods, fluctuations in annual water loss are smaller and closely follow the pattern in annual total radiation (Figure 3.24).

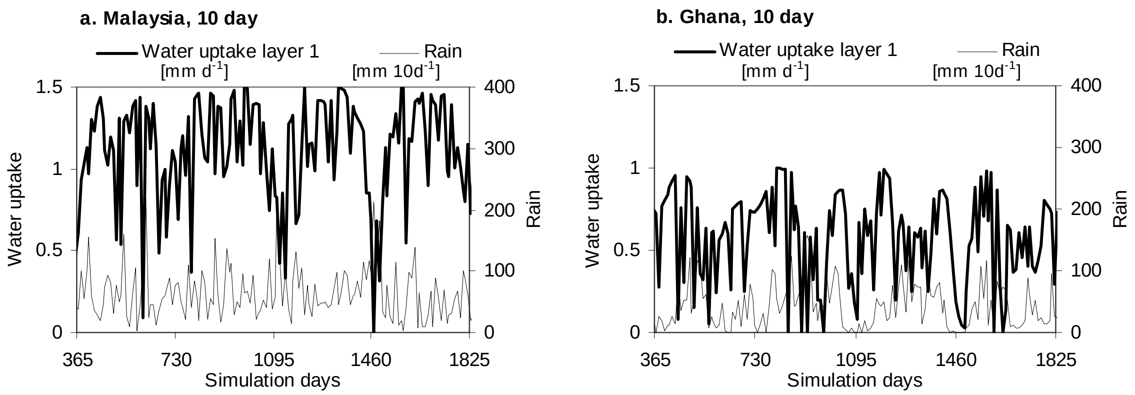


Figure 3.20. Example simulation output for the water content (volume percentage) in the first soil layer, compared to rain fall, for Malaysia (a) and Ghana (b). Characteristics of this soil layer are provided in Table 3.1. Simulation results for 10-day periods are shown for years 2-5 of the simulations. Program variable names: Water content layer 1=WCLQT(1); Rain=D10RAIN.

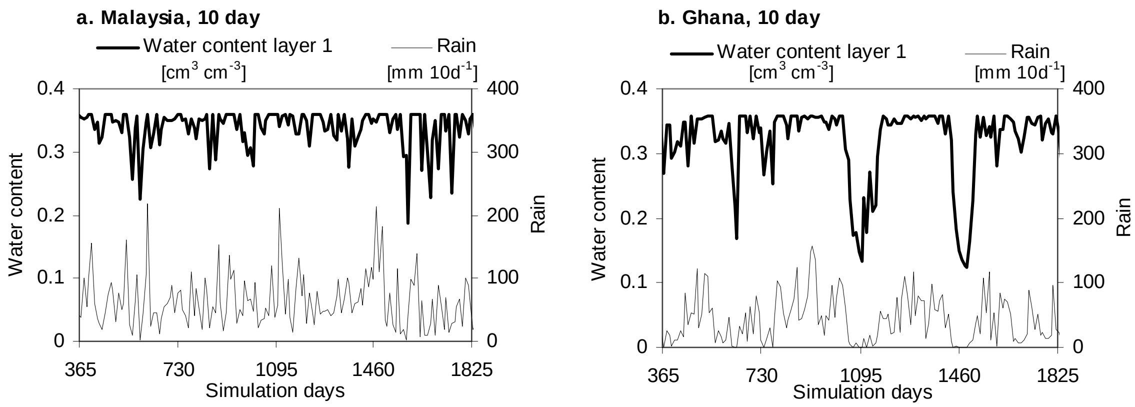


Figure 3.21. Example simulation output for the water uptake from the first soil layer, compared to rain fall, for Malaysia (a) and Ghana (b). Characteristics of this soil layer are provided in Table 3.1. Simulation results for 10-day periods are shown for years 2-5 of the simulations. Program variable names: Water uptake layer 1=TRWL(1); Rain=D10RAIN.

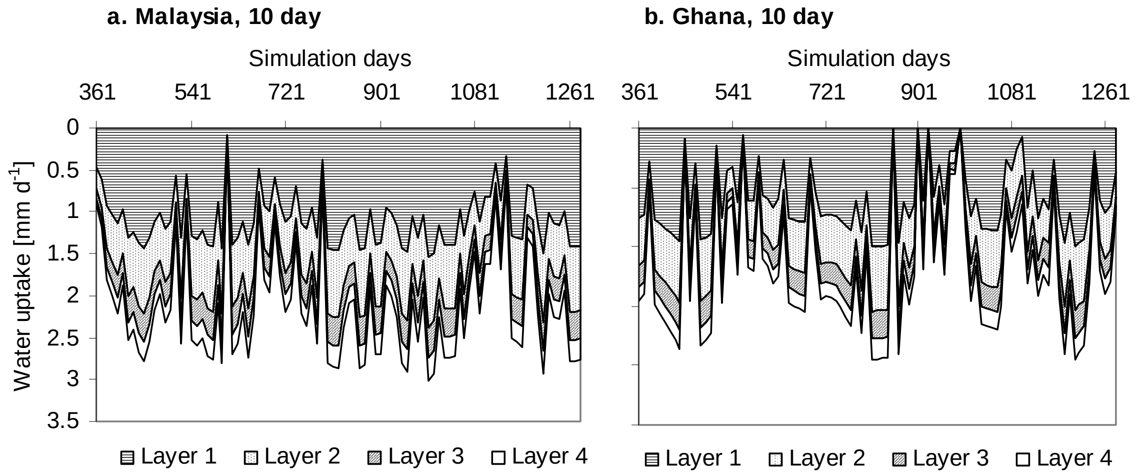


Figure 3.22. Example simulation output for the water uptake from four soil layers, for Malaysia (a) and Ghana (b). Characteristics of the soil layers are provided in Table 3.1. Simulation results for 10-day periods are shown for years 2-3.5 of the simulations. Program variable names: Water uptake layer x = TRWL(x).

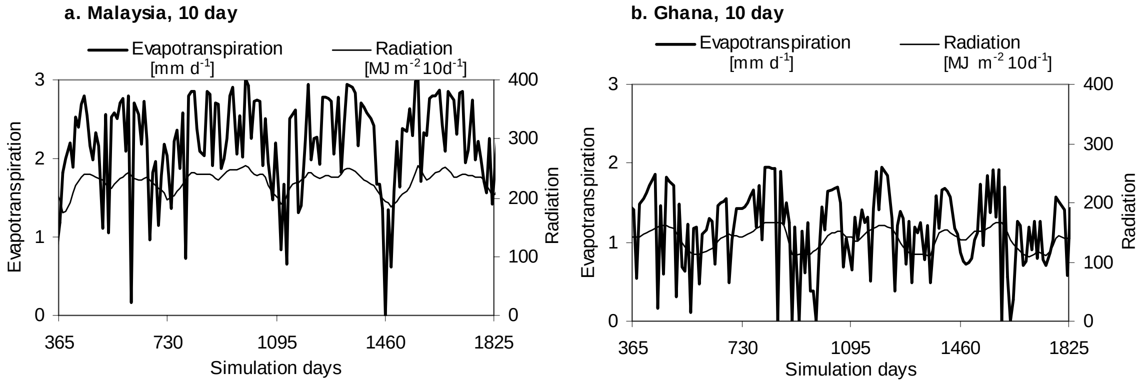


Figure 3.23. Example simulation output for total evapotranspiration, compared to radiation, for Malaysia (a) and Ghana (b). Simulation results for 10-day periods are shown for years 2-5 of the simulations. Program variable names: Evapotranspiration = ATRANS; Rain=D10RDD.

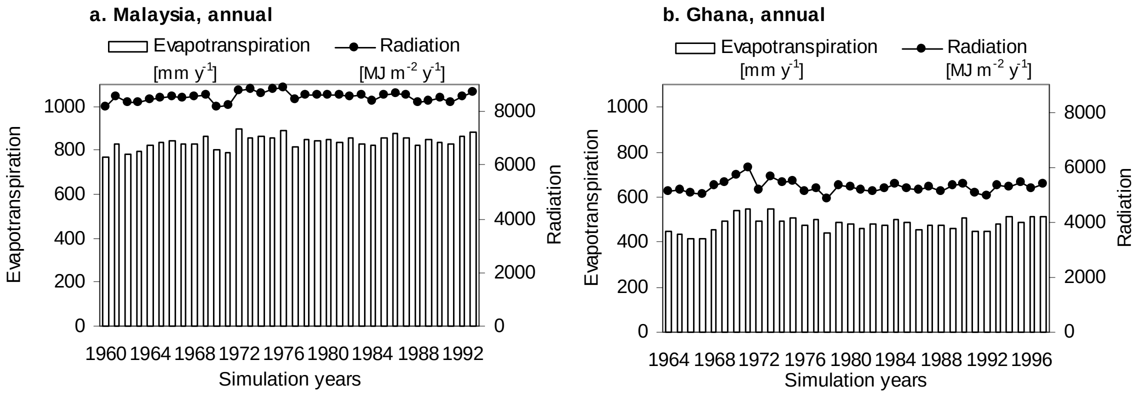


Figure 3.24. Example simulation output for the total evapotranspiration compared to radiation, for Malaysia (a) and Ghana (b). Total annual values are shown for years 2-35 of the simulations. Program variable names: Evapotranspiration = YTRANS; Radiation = YRDD.

4. Model validation

4.1 Purpose

The purpose of model validation is to evaluate to what extent model predictions match the values observed in reality. When case model results are very different from observed values, there is a need to modify calculations or input parameter values in the model or calibrate the model in order to obtain better agreement.

4.2 Approach

Comprehensive sets of yield and climate data for the same period of time are very scarce for cocoa. Such data sets allow for model validation in which simulated yields are compared with observed yields over a period of time. Currently, only one such data set is available to us (for Sabah, Malaysia), but without information on shade regime. We have chosen to carry out model validation for average values over time and using a number of output parameters generated by the model. These were: bean yield, standing biomass, biomass production, leaf area index, litter production and age-size relationship. For these output parameters, field measurements or estimates were available. The simulated values of these output parameters are compared to field observations. When possible, simulations are carried out for the same location or country where field observations were conducted. Parameter values used for the simulation are the same as used for the simulations described in Chapter 3 (see Section 3.2), apart from simulations for bean yield, which were carried out for a situation without shade trees. Simulations are done for water-limited production.
In general, simulated values are expected to be higher than the observed values as in CASE2 the incidence of pests and diseases is not taken into account and there are no limitations of nutrients.

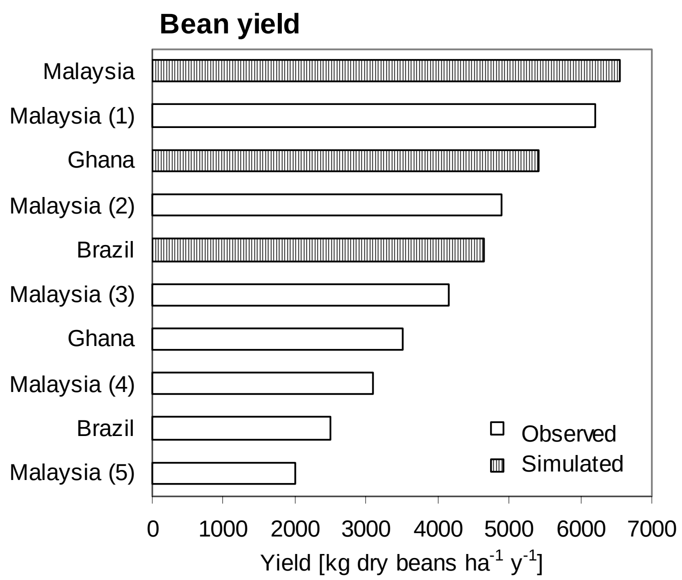


Figure 4.1. Comparison of simulated and observed bean yield for cocoa in different regions. Simulated yields are calculated using CASE2 v2.2 (no shade, planting density = 1000 trees ha^{-1}, starting age = 1500 days). The average yield of trees ageing 5-15 years was used. Simulations were carried out for Tawau (Malaysia, 1984-1993), Tafo (Ghana, 1988-1997) and Alagoas (Brazil, 1964-1969). Observed values are taken from Yapp & Hadley, 1994 (Malaysia (1)), Lim & Pang 1990 (Malaysia (2)), Lim 1980 (Malaysia (3)), Ahenkorah, 1974 (Ghana), Palaniappan & Shuhaimi, 1990 (Malaysia (4)), Alvim & Nair, 1986 (Brazil) and Lim 1994 (Malaysia (5)).

4.3 Bean yield

Bean yield values simulated using CASE2 are compared with the highest observed yields in experimental plantations in different regions. In this case simulations have been carried out for a situation without shade trees, as the observed yields are reached in plantations without shading. Figure 4.1 shows the results of this comparison. Tree age was generally 5-10 years, planting density varied considerably: from 1000 trees ha^{-1} for the simulations to 3333 tree ha^{-1} for two of the Malaysian sites. It can be observed that for each of the regions (Malaysia, Brazil and Ghana), simulated yields (hatched bars) are always higher than the highest observed yields. For Malaysia the difference between simulated and observed yields is relatively small, but simulated values for Ghana and Brazil are 50 and 80% higher than observed. In general there is a good agreement of simulated and harvested yields, especially when considering that CASE2 is a globally applicable model, which is not specifically calibrated for one specific location or hybrid.

4.4 Standing biomass

Estimates of standing biomass (dry weight or dry matter) in cocoa plantations have been made for several regions. In most cases the biomass estimates are based on measurements of the biomass of a (small) number of cacao trees that were entirely harvested. Observed and simulated values for standing biomass are compared in Figure 4.2. Two of the observed values are clearly much higher than the simulated values and the remaining observed values. The values for Malaysia (1) and (2) overestimate the standing biomass as they were based on biomass measurements of the larger trees in the plantation (Thong & Ng 1980). The value for Nigeria is an indirect - and therefore rough - estimate based on relations between trunk diameter and biomass. Furthermore, both density and age of the trees in this plantation were high (1667 trees ha^{-1} and 22 y), compared to the other plantations (density 900-1100 trees ha^{-1} and tree age 5-10 y). The simulated values are close to the other observed values, both for Malaysia and Costa Rica. In the latter case, the observed value is somewhat higher than the simulated value.

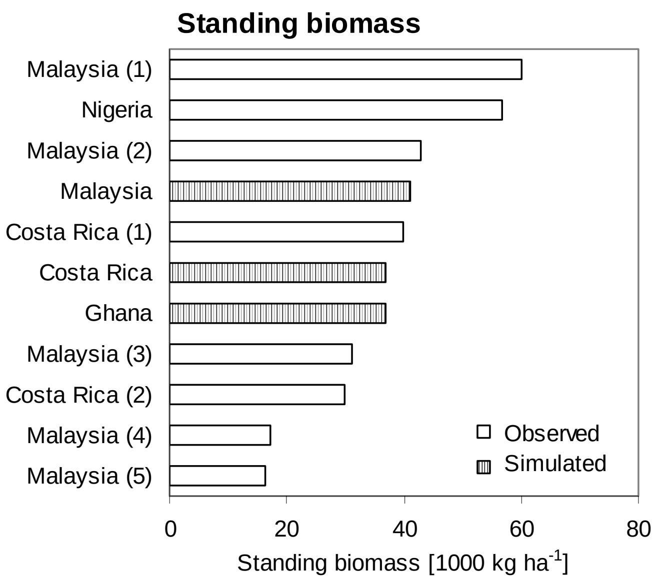


Figure 4.2. Comparison of simulated and observed standing total biomass (dry weight or dry matter) of cocoa stands in different regions. Simulated biomass values are calculated using CASE2 v2.2 (ca. 10% shade, planting density = 1000 trees ha^{-1}, starting age = 1500 days). The simulated values are for trees aged 10 years. Simulations were carried out for Tawau (Malaysia), Tafo (Ghana) and Alagoas (Brazil). Observed values are taken from Thong & Ng 1979 (Malaysia (1 and 2)), Opakunle 1991 (Nigeria), Beer *et al.* 1990 (Costa Rica (1 and 2)) and Teoh *et al.*; 1986 (Malaysia 3-5).

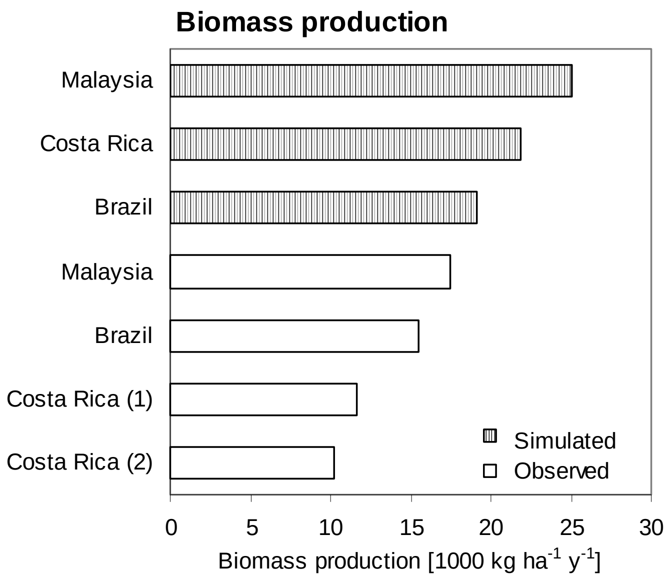


Figure 4.3. Comparison of simulated and observed values for biomass production (in dry weight) of cocoa stands in different regions. Simulated biomass values are calculated using CASE2 v2.2 (ca. 10% shade, planting density = 1000 trees ha^{-1}, starting age = 1500 days). The simulated values are for trees aged 10 years. Simulations were carried out for Tawau (Malaysia), El Carmen (Costa Rica) and Alagoas (Brazil). Observed values are taken from Thong & Ng 1980 (Malaysia), Alvim 1977 (Brazil), and Beer *et al.* 1990 (Costa Rica (1 and 2).

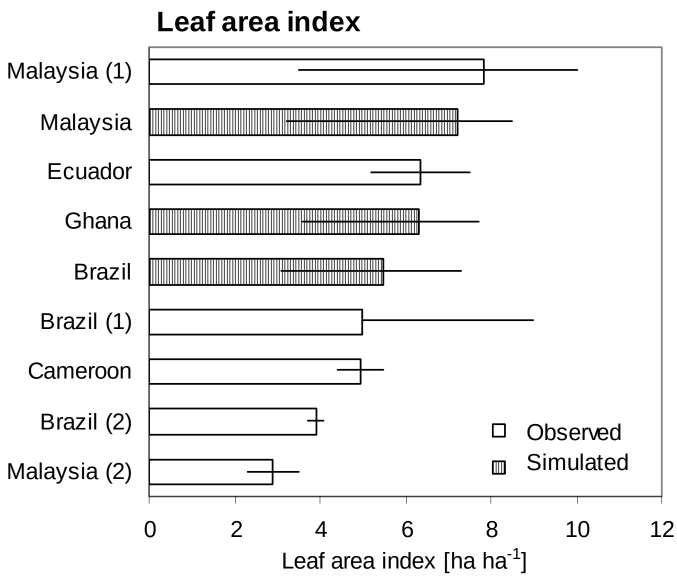


Figure 4.4. Comparison of simulated and observed values for leaf area index of cocoa stands in different regions. Bars denote average values; error bars indicate range (minimum and maximum values). Simulated biomass values are calculated using CASE2 v2.2 (ca. 10% shade, planting density = 1000 trees ha^{-1}, starting age = 1500 days). The simulated values are for trees of 5-10 years. Simulations were carried out for Tawau (Malaysia), El Carmen (Costa Rica) and Alagoas (Brazil). Observed values are taken from Thong & Ng 1980 (Malaysia (1)), Hadfield 1981 (Ecuador), Alvim, 1967 (Brazil (1)), Boyer 1970 (Cameroon) and Miyaji *et al.* 1997 (Brazil (2)). The maximum values for Cameroon and Brazil (2) are for unshaded cocoa; all others for shaded plantations.

4.5 Biomass production

Field measurements on biomass production (or dry matter production) for cocoa are scarce, and available values are often based on estimates instead of actual measurements of biomass. Only the long-term study on dry matter production in two shaded cocoa systems in Costa Rica is well documented. When comparing observed and simulated values for biomass production, simulated values are clearly higher than observed values. This is especially the case for Costa Rica with a factor two difference between observed and simulated. For Malaysia and Brazil observed values are 20-30% lower than simulated.

4.6 Leaf area index (LAI)

The leaf area index (LAI) is the number of leaf layers in the cocoa canopy. It is an important intermediate result of the simulation model, as it determines the interception of light and thus the gross photosynthesis and ultimately the biomass production. The leaf area index of the cocoa crop

depends – among others – on the amount of shading. In unshaded cocoa, the cocoa crop may form more layers of leaves as more light is available above the cocoa canopy. Under heavy shade, it is not ”profitable” for cacao trees to form many layers of leaves: in that case the amount of light penetrating through one or two layers of cocoa leaves is not sufficient for photosynthesis. The maximum LAI value observed in cocoa plantations is 10 ha ha^{-1} (or m^2 m^{-2}). Another factor that influences LAI is the amount and distribution of rainfall: during dry months, cacao trees may loose a substantial part of their leaves, thus attaining a lower LAI value.
Comparison of simulated and observed LAI values in Figure 4.4 shows a good agreement between the two. The high Malaysian values are based on leaf area measurements for large (thus non-representative) trees in the study plantation, and are therefore likely to overestimate the average value in that plantation. Simulated values for unshaded cocoa are higher than those presented in Figure 4.4, up to 9.3 ha ha^{-1} for Malaysia and 8.5 ha ha^{-1} for Ghana.

4.7 Litter production

A comparison of simulated and observed values for leaf litter production (Figure 4.5) shows rather large differences between the two. Simulated litter production for Malaysia was twice the observed amount; and for West-African conditions, simulated values for Ghana were around three times as high as those observed in Cameroon. There are two possible explanations for these differences. First, the production of leaf litter strongly depends on the life span of the leaves: if leaves have a short leaf span, leaf turn-over is high and – as a result – leaf production and leaf loss are high. In CASE2, the average leaf life span is set to 210 days (based on a study in Brazil, Miyaji *et al.* 1997a), which is lower than estimates obtained in other studies. Nevertheless, the Brazilian study is the only study in which leaf life span is actually determined. Secondly, the leaf life span and thus the litter production depends on the amount of light received by cacao leaves. Leaves of shaded cacao trees have a longer life span than those of unshaded trees, and leaves low in the cacao canopy have a longer life span than those in the upper layers. In CASE2, the light-dependency of leaf life span is not included, and the value for leaf life span is probably more realistic for plantations with no or little shade than for those with moderate or heavy shading. Several of the observed values for litter production were obtained for cocoa under “moderate” shade (Malaysia, Costa Rica, Venezuela), whereas the simulations were carried out for light shading (with on average 10% of the incoming

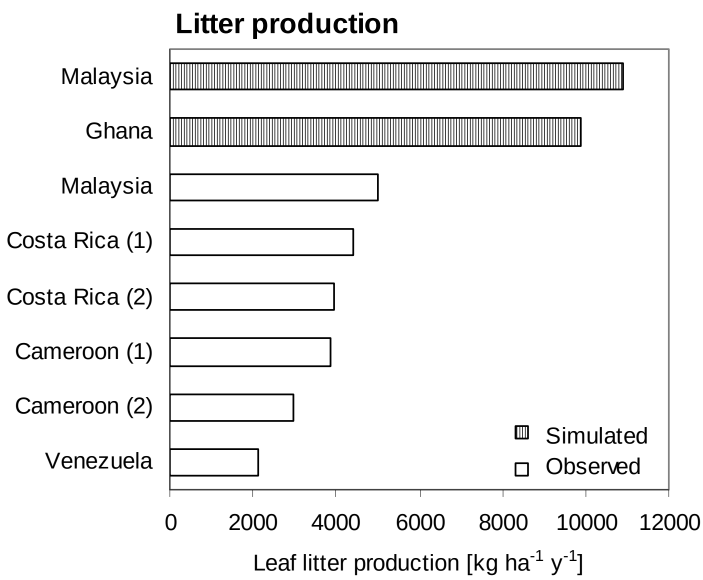


Figure 4.5. Comparison of simulated and observed values for leaf litter production in cocoa stands in different regions. Simulated biomass values are calculated using CASE2 v2.2 (ca. 10% shade, planting density = 1000 trees ha^{-1}, starting age = 1500 days). The simulated values are for trees of 10 years. Simulations were carried out for Tawau (Malaysia) and Tafo (Ghana). Observed values are taken from Ling 1986 (Malaysia), Beer *et al.* 1990 (Costa Rica (1 and 2)), Boyer 1973 (Cameroon (1 and 2)) and Arangueren *et al.* 1982 (Venezuela).

radiation being intercepted by shade trees). An increase in shading to moderate shade (45%) in the model results in a considerable decline of one third in litter production (for Tawau, Malaysia).

4.8 Age-size relation

Age of model cacao trees does not affect simulated processes in CASE2: it does not determine any of the physiological processes simulated in the model. Instead of the age of a tree, its biomass is used as a feedback variable: the biomass of the tree determines (indirectly) the rate of photosynthesis, the amount of assimilates required for respiration, the partitioning of assimilates over different plant organs, etc.. Only for the initialisation of the model (determining the initial values used by the model), tree age is used. The relation between age and size obtained in the simulations can thus be compared to the same relation established for real cacao trees, as these two relations are independent. In a number of studies, the biomass (dry weight) of entire cacao trees has been measured. As the age of these harvested trees is usually known, a relation between tree age and weight can be established.
Observed and simulated age-size relations are shown in Figure 4.6. It is clear that there exists a very large variation in the total biomass of similarly-aged trees: the dry weight of trees 5-10 years old varied from less than 10 kg to over 50 kg. Part of this variability may be explained by the difference in climate and cropping system among the data points: some of the measured trees were located in favourable and others in unfavourable climates, some had grown without shade and others with moderate to heavy shade. The simulations for lightly shaded (10%) cocoa in Malaysia and Ghana produce larger cacao trees than the average observed tree (indicated by the regression line in the Figure). Nevertheless, given the large variation in observed values, the simulated values are still within the range of observed values. The simulated age-size relation depends strongly on the level of shading. When shading is increased to 50%, the simulated lines follow almost completely the average observed regression line (this is not shown in the Figure).

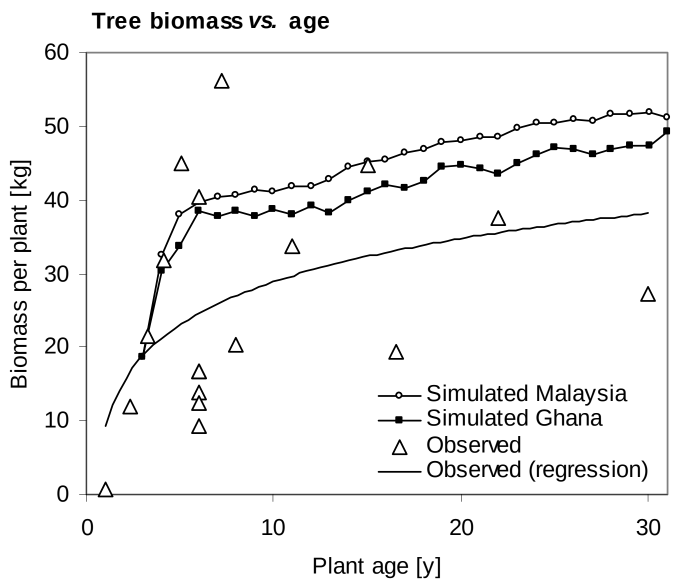


Figure 4.6. Comparison of simulated and observed age-size relationships in cocoa stands in different regions. Simulated biomass values are calculated using CASE2 v2.2 (ca. 10% shade, planting density = 1000 trees ha^{-1}, starting age = 1500 days). The simulated values are for trees of 3-30 years. Simulations were carried out for Tawau (Malaysia) and Tafo (Ghana). Observed values are taken from Aranguren *et al.* 1982, Himme 1959, Opakunle 1991, Subler 1994, Teoh *et al.*; 1986, and Thong & Ng 1980. The non-linear regression line for observed values explains 20% of the variation in total weight (y = 7.22* Ln(x) + 1.29).

4.9 Concluding remarks

Considering the results of the validation analysis, it becomes clear that, in general, there is a good agreement of model results with observed values, especially for bean yield, biomass production and leaf area index. The largest differences between observed and simulated values was found for litter production, and is probably related to differences in shade regime, standing biomass and leaf dynamics between observed and simulated situations. The lack of quantitative information on shading and standing biomass for the field studies that reported on litter fall makes a good comparison difficult.

5. Sensitivity analysis

5.1 Purpose

The purpose of the sensitivity analysis is to identify those input parameters of the model that have the largest influence on model output in terms of estimated yield and biomass production. Sensitivity analysis thus also indicates which parameters should be accurately quantified as small changes in such parameters may have a large impact on model output.

5.2 Approach

Sensitivity analyses are carried out by changing an input parameter and assessing the effect of this change on model output. Input parameters are changed with respect to the standard value of the parameter – a proportional change – and the change in output is also considered in relation to its value using the standard input. For the purpose of this report, two output parameters were selected: annual yield of dry, fermented beans (program variable name: YYLDBN) and annual biomass production (YGTOT), but the analysis can also be carried out for other parameters. Simulation runs for the sensitivity analysis were carried out over a period of 11 years. The output of the first year of this simulation was not used to allow the model to adapt to the environmental conditions. The output of the following 10 years was averaged and then compared to the average output using standard input values. The analysis was carried out for two sites: Tawau, Sabah in Malaysia (period 1983-1993) and Tafo in Ghana (1987-1997).
All relevant input parameters (75 in total) were varied by adding and subtracting 10% of their standard value. Weather-related variables were also varied by adding and subtracting 10% of values for temperature (Program variable name: TMMN and TMMX), radiation (RDD) and rain fall (RAIN). Soil characteristics were varied by applying 10% changes in the “maximum” water content (“field capacity”, WCFC) and lowest water content at which water can be extracted (“wilting point”, WCWP). Only one parameter was changed at a time. For all other parameters standard values were used (see Section 3.2 for values of the input parameters that may be changed by the user).

Thus, in detail the procedure was as follows: (1) the value of an input parameters was changed, (2) a simulation run was carried out using this changed parameter, (3) the simulation output for annual bean yield and total biomass were obtained, (4) an average value of the output was computed for simulation years 2-11; and (5) the newly obtained value was compared to the standard value and the relative change computed.

5.3 Results for bean yield

Figure 5.1 shows the results of the sensitivity analysis for bean yield. Black bars in this graph denote the ten input parameters causing the largest positive (upper 10 bars) and the ten parameters causing the largest negative (lower 10 bars) changes in bean yield. Hatched bars show the effect of a 10% decrease in the value of the input parameter on bean yield. The description of the type of parameter provided in the graph shows that for both Malaysia and Ghana, similar parameters are important in determining bean yield. Parameters related to radiation,

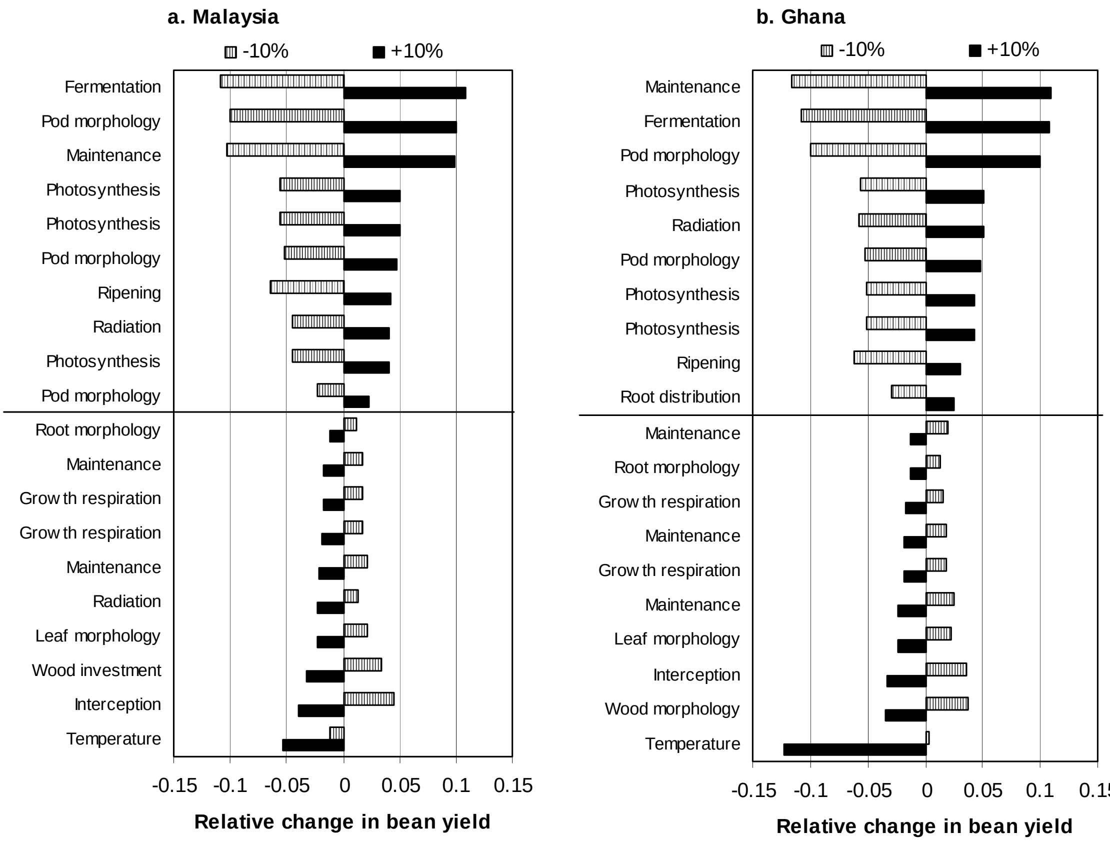


Figure 5.1. Results of a sensitivity analysis of CASE2 for the output parameter dry, fermented bean yield (YYLDBN), for Malaysia (a) and Ghana (b). Black bars denote the relative change in bean yield due to a 10% increase in the input parameter along the y-axis. The black bars above the drawn line represent the 10 parameters that lead to the highest increase in bean yield. The black bars below the line represent the 10 parameters that lead to the highest decrease in bean yield. Hatched bars denote relative changes in bean yield due to a 10% decrease of each input parameter. For clarity, only the type of parameter (maintenance, interception etc.) is mentioned here. A description of the parameters shown in these graphs is provided in Table 5.1. See Section 5.2 for an explanation on the methodology used.

photosynthesis, maintenance respiration, pod morphology, pod ripening and fermentation of beans have a strong positive impact on bean yield when their value is increased by 10%. For Ghana, the distribution of roots also belongs to the top-10 of important parameters. This is most probably related to the fact that water availability is limiting bean production in Ghana more than in Malaysia, and that a different distribution of roots within the soil would have a positive effect on water uptake by cacao trees in Ghana.
Changes in bean yield resulting from a +10% (black bars in Figure 5.1) and a –10% (hatched bars) change in input parameters are comparable for most parameters. This suggests that the relation between most input and bean yield is approximately linear, at least for this interval. A notable exception is average temperature, which has a negative impact on bean yield when increased by 10% and also has a negative impact when decreased by 10% in the case of Malaysia. This is related to the fact that lower temperatures decrease maintenance costs but also decrease fruit ripening.

A detailed description of the most important input parameters is provided in Table 5.1. Comparing the top-10 parameters between the two locations, reveals that that 9 out of the 10 parameters with large positive effects on yield are the same for Malaysia and Ghana. Thus, in spite of the significant differences in climatic conditions, the same conclusions can be drawn from this analysis for both countries. A closer look at the most important parameters with a positive effect shows that most can be grouped into two broad categories. (1) Parameters related to the primary process of light interception and photosynthesis. Increases in the maximum rate of photosynthesis, the initial photosynthetic efficiency and the fraction of photosynthetically active radiation all have strong influence on the production of assimilates which can later be used for pod production (and finally bean yield). (2) The second group of parameters relates to the pods and beans. Investment in pods, their development rate and the amount of bean weight lost due to fermentation all have direct influence on the bean yield.

Strong negative impact on bean yield is achieved by adding 10% to the value of parameters related to light interception, maintenance, growth respiration, morphology of roots, leaves and wood, and to temperature. Again, these are generally the same for Malaysia and Ghana. For Malaysia, in addition to these parameters, also an increase in radiation causes a decrease in bean yield. This can most probably be explained by the high level of radiation in Malaysia: at this high level, the maximum photosynthesis is often reached, and an increase in radiation does not lead to an increase in the production of assimilates. In fact, the higher radiation may have a negative effect as it increases the heating of the tree, thus requiring more transpiration, which may in some cases lead to water shortage and therefore lower photosynthesis. This, in turn, will decrease bean yield.

A similar grouping can be carried out for the parameters that have a strong negative effect on bean yield. Three groups of parameters can be distinguished. (1) Parameters related to maintenance costs. Increases in the maintenance requirements of leaves and wood cause a decrease in bean yield, as less assimilates are available for net growth of plant organs, and thus for pods. (2) Parameters related to growth costs. A certain amount of assimilates is required to increase the weight of a certain organ. If these requirements are increased by 10%, the weight increment of the organ will be smaller and, as a results, bean harvest will be lower. (3) Investment in non-harvestable parts. In CASE2 growth of plant parts depends on information about the distribution of biomass over plant parts. Changing the regression coefficient that specifies the biomass of one plant part relative to the total biomass, will modify the biomass invested in that plant part. An increase in the regression coefficient for wood, leaves or roots causes an increase in biomass of these organs, and – due to the limited availability of assimilates – a decrease in the investment in pods.

In addition to these three groups, there are two parameters with strong negative impact: average temperature and the light extinction coefficient. Temperature has an influence on several processes in the model: maintenance respiration, pod ripening, transpiration rate and – in case of extreme temperatures – photosynthesis. Most probably, the strong negative effect is caused by extra maintenance costs: at temperature above a reference temperature (25°C), maintenance costs are strongly increased, thus leaving less assimilates for biomass production and pod growth. The light extinction coefficient determines the part of incoming radiation that is transmitted by one layer of leaves. An increase in this value implies that less light is transmitted per leaf layer and – as a consequence – that photosynthesis and biomass production and pod growth are reduced.

Finally, as a general remark, it becomes clear from the results of the sensitivity analysis that none of the parameters has a very strong impact on bean yield. Only three parameters cause changes of more than +10 or –10% in bean yield. Increases of 10% in the values of the top-10 parameters only lead to an average 6% increase in bean yield.

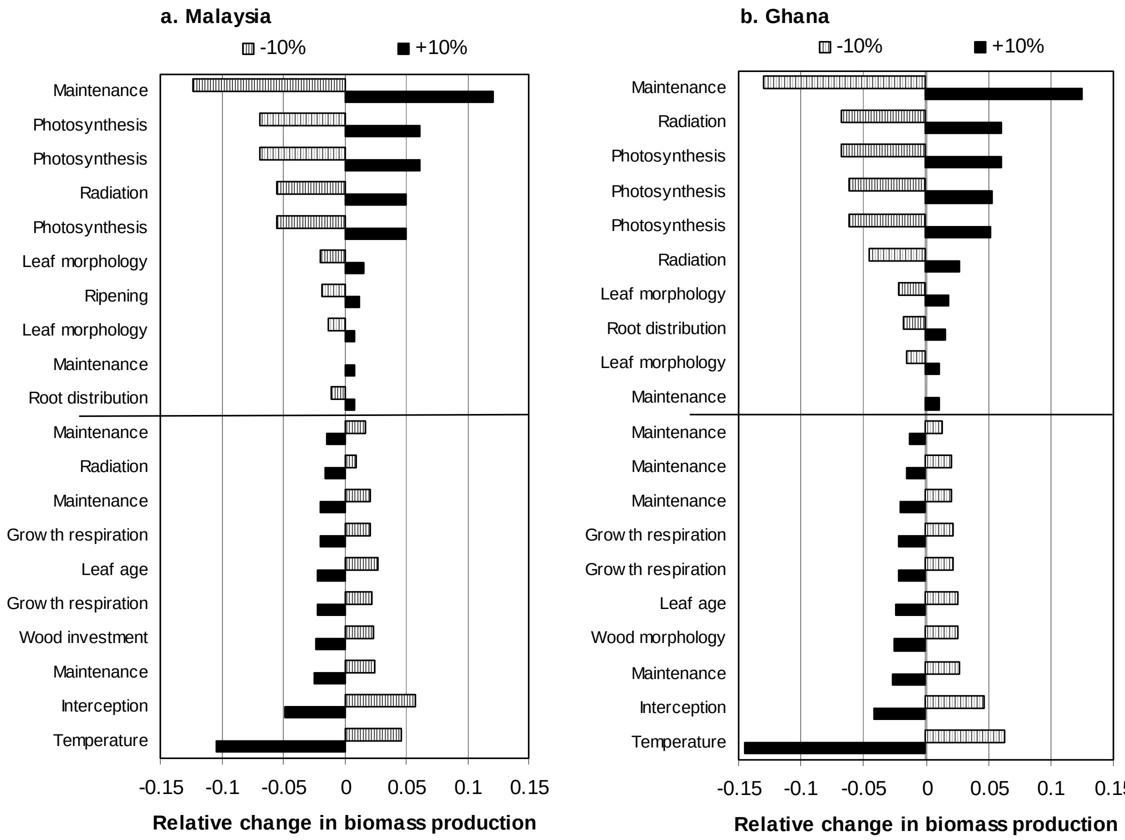


Figure 5.2. Results of a sensitivity analysis of CASE2 for the output parameter total biomass production (YGTOT), for Malaysia (a) and Ghana (b). Black bars denote the relative change in biomass production due to a 10% increase in the input parameter along the y-axis. The black bars above the drawn line represent the 10 parameters that lead to the highest increase in biomass production. The black bars below the line represent the 10 parameters that lead to the highest decrease in biomass production. Hatched bars denote relative changes in biomass production due to a 10% decrease of each input parameter. For clarity, only the type of parameter (maintenance, interception etc.) is mentioned here. A full description of the parameters shown in these graphs is provided in Table 5.2. See Section 5.2 for an explanation on the methodology used.

5.4 Results for total biomass production

Figure 5.2 shows the results of the sensitivity analysis for biomass production. Black bars in this graph denote the ten input parameters causing the largest positive (upper 10 bars) and the ten parameters causing the largest negative (lower 10 bars) changes in biomass production. Comparing the black bars in parts a and b of Figure 5.2, it appears that for both Malaysia and Ghana, similar parameters are important in determining biomass production. Parameters related to radiation, photosynthesis, maintenance respiration, leaf morphology and root distribution have a strong positive impact on biomass production when their value is increased by 10%. For Ghana, the amount of radiation also has a strong positive effect on biomass production. This is most probably related to the fact that radiation in Ghana is low compared to Malaysia (see Figure 3.1 for comparison), and that an increase in radiation in Ghana leads to an increase in photosynthesis, and thus to a higher biomass production. In Malaysia, radiation is often at a level at which the maximum rate of photosynthesis is reached. (In fact, a 10% increase in radiation for Malaysia has a negative effect on biomass production.) For Malaysia, the development rate of pods also has a positive effect on biomass production. This may be related to the fact that when pods ripen quickly,

Table 5.1. List of most important input parameters determining bean yield, for Malaysia (a) and Ghana (b). Parameters and their order are the same as in Figure 5.1. Parameters having a positive effect (+) on bean yield when increased by 10% are ranked from 1-10 and those with a negative effect from 10-1. Code refers to the parameter code in CASE2.

	Category	Code	Description
	a. Malaysia		
+	Fermentation	FMTB	Regression coefficient on biomass loss due to fermentation
+	Pod morphology	FBEANS	Dry weight fraction of beans in pod
+	Maintenance	TREF	Reference temperature for calculation of maintenance respiration
+	Photosynthesis	AMX	Maximum rate of photosynthesis
+	Photosynthesis	AMINIT	Factor accounting for lower photosynthesis in young leaves
+	Pod morphology	FPDRA	Regression coefficient on relation between pod and total biomass
+	Ripening	DEVRR2A	Regression coefficient on relation between temperature and pod ripening
+	Radiation	FRPAR	Fraction of photosynthetically active radiation (PAR)
+	Photosynthesis	EFF	Increase in photosynthesis with increase in radiation at low radiation
+	Pod morphology	FPDRB	Regression coefficient on relation between pod and total biomass
-	Root morphology	FLRTRA	Regression coefficient on relation between root and total biomass
-	Maintenance	MAINLV	Maintenance requirements for leaves
-	Growth respiration	ASRQLV	Assimilate requirements for the production of leaves
-	Growth respiration	ASRQPDTB	Assimilate requirements for the production of pods
-	Maintenance	MAINWD	Maintenance requirements for wood
-	Radiation	RDD	Radiation
-	Leaf morphology	FLVRA	Regression coefficient on relation between leaf and total biomass
-	Wood investment	FWDRA	Regression coefficient on relation between wood and total biomass
-	Interception	KDFL	Extinction coefficient of leaves
-	Temperature	TM	Average temperature
	b. Ghana		
+	Maintenance	TREF	Reference temperature for calculation of maintenance respiration
+	Fermentation	FMTB	Regression coefficient on biomass loss due to fermentation
+	Pod morphology	FBEANS	Dry weight fraction of beans in pod
+	Photosynthesis	EFF	Increase in photosynthesis with increase in radiation at low radiation
+	Radiation	FRPAR	Fraction of photosynthetically active radiation (PAR)
+	Pod morphology	FPDRA	Regression coefficient on relation between pod and total biomass
+	Photosynthesis	AMX	Maximum rate of photosynthesis
+	Photosynthesis	AMINIT	Factor accounting for lower photosynthesis in young leaves
+	Ripening	DEVRR2A	Regression coefficient on relation between temperature and pod ripening
+	Root distribution	VDWURTRA	Regression coefficient on vertical distribution of fine roots
-	Maintenance	HRTWDAGE	Age at which softwood is transformed into non-respiring heartwood
-	Root morphology	FLRTRA	Regression coefficient on relation between root and total biomass
-	Growth respiration	ASRQPDTB	Assimilate requirements for the production of pods
-	Maintenance	MAINLV	Maintenance requirements for leaves
-	Growth respiration	ASRQLV	Assimilate requirements for the production of leaves
-	Maintenance	MAINWD	Maintenance requirements for wood
-	Leaf morphology	FLVRA	Regression coefficient on relation between leaf and total biomass
-	Interception	KDFL	Extinction coefficient of leaves
-	Wood morphology	FWDRA	Regression coefficient on relation between wood and total biomass
-	Temperature	TM	Average temperature

Table 5.2. List of most important input parameters determining total biomass production, for Malaysia (a) and Ghana (b). Parameters and their order are the same as in Figure 5.2. Parameters having a positive effect (+) on biomass production when increased by 10% are ranked from 1-10 and those with a negative effect from 10-1. Code refers to the parameter code in CASE2.

	a. Malaysia		
	Category	Code	Description
+	Maintenance	TREF	Reference temperature for calculation of maintenance respiration
+	Photosynthesis	AMX	Maximum rate of photosynthesis
+	Photosynthesis	AMINIT	Factor accounting for lower photosynthesis in young leaves
+	Radiation	FRPAR	Fraction of photosynthetically active radiation (PAR)
+	Photos	EFF	Increase in photosynthesis with increase in radiation at low radiation
+	Leaf morphology	FLVRA	Regression coefficient on relation between leaf and total biomass
+	Ripening	DEVRR2A	Regression coefficient on relation between temperature and pod ripening
+	Leaf morphology	SLARB	Regression coefficient on leaf area per unit leaf biomass
+	Maintenance	CFWD	Carbon fraction in wood
+	Root distr	VDWURTRA	Regression coefficient on vertical distribution of fine roots
-	Maintenance	HRTWDAGE	Age at which softwood is transformed into non-respiring heartwood
-	Radiation	RDD	Radiation
-	Maintenance	MAINLV	Maintenance requirements for leaves
-	Growth respiration	ASRQLV	Assimilate requirements for the production of leaves
-	Leaf age	AVGLAG	Average leaf age
-	Growth respiration	ASRQPDTB	Assimilate requirements for the production of pods
-	Wood investment	FWDRA	Regression coefficient on relation between wood and total biomass
-	Maintenance	MAINWD	Maintenance requirements for wood
-	Interception	KDFL	Extinction coefficient of leaves
-	Temperature	TM	Average temperature
	b. Ghana		
+	Maintenance	TREF	Reference temperature for calculation of maintenance respiration
+	Radiation	FRPAR	Fraction of photosynthetically active radiation (PAR)
+	Photosynthesis	EFF	Increase in photosynthesis with increase in radiation at low radiation
+	Photosynthesis	AMX	Maximum rate of photosynthesis
+	Photosynthesis	AMINIT	Factor accounting for lower photosynthesis in young leaves
+	Radiation	RDD	Radiation
+	Leaf morphology	FLVRA	Regression coefficient on relation between leaf and total biomass
+	Root distribution	VDWURTRA	Regression coefficient on vertical distribution of fine roots
+	Leaf morphology	SLARB	Regression coefficient on leaf area per unit leaf biomass
+	Maintenance	CFWD	Carbon fraction in wood
-	Maintenance	MAINLRT	Maintenance requirements for lateral roots
-	Maintenance	HRTWDAGE	Age at which softwood is transformed into non-respiring heartwood
-	Maintenance	MAINLV	Maintenance requirements for leaves
-	Growth respiration	ASRQPDTB	Assimilate requirements for the production of pods
-	Growth respiration	ASRQLV	Assimilate requirements for the production of leaves
-	Leaf age	AVGLAG	Average leaf age
-	Wood morphology	FWDRA	Regression coefficient on relation between wood and total biomass
-	Maintenance	MAINWD	Maintenance requirements for wood
-	Interception	KDFL	Extinction coefficient of leaves
-	Temperature	TM	Average temperature

they require less maintenance respiration as they are attached to the tree for a shorter period of time. A reduction in maintenance respiration leads to more tree growth and thus more biomass production.

A detailed description of the most important input parameters is provided in Table 5.2. Comparing the top-10 parameters between the two locations, reveals that that 9 out of the 10 parameters with large positive effects on yield are the same for Malaysia and Ghana. This is also the case for parameters that have a strong negative effect on yield (when increased by 10%): also here 9 out of 10 parameters are the same for Malaysia and Ghana. Thus, the same conclusions can be drawn from this analysis for both countries. Similar correspondence between results of the two countries were found in the sensitivity analysis of bean yield (Section 5.3).

Similar to what was done in Section 5.3 on the sensitivity analysis for bean yield, the most important parameters can now be grouped into categories. Two broad categories are distinguished. (1) Six out of the ten parameters are related to the primary process of light interception and photosynthesis. Increases in the maximum rate of photosynthesis, the leaf area, the initial photosynthetic efficiency and the fraction of photosynthetically active radiation all have strong influence on the production of assimilates and thus for biomass production. (2) Maintenance respiration. The reference temperature to determine the temperature-related increase in maintenance costs is the most important for both Malaysia and Ghana. A 10% increase in this parameter strongly decreases maintenance respiration and therefore increases the production of biomass.
Strong negative impact on biomass production is achieved by adding 10% to the value of parameters related to light interception, maintenance, growth respiration, wood morphology, leaf age and temperature. Again, these are generally the same for Malaysia and Ghana. For Malaysia, in addition to these parameters, also an increase in radiation causes a decrease in biomass production. As mentioned above, this can be attributed to the high level of radiation in Malaysia.

Groups of parameters with a strong negative impact on biomass production can be identified. Two groups are distinguished. (1) Parameters related to maintenance costs. Increases in the maintenance requirements of leaves and wood cause a decrease in biomass production, as less assimilates are available for the growth of plant organs. (2) Parameters related to growth costs. A certain amount of assimilates is requires to increase the weight of a certain organ. If these requirements are increased, the weight increment of the organ will be smaller causing a dip in biomass production.

In addition to these two groups (and similar to the results for the bean yield sensitivity analysis, Section 5.3), there are two parameters with strong negative impact: average temperature and the light extinction coefficient. Temperature has an influence on several processes in the model: maintenance respiration, pod ripening, transpiration and – in case of extreme temperatures – photosynthesis. Most probably, the strong negative effect is caused by extra maintenance costs: at temperature above a reference temperature (25ºC), maintenance costs are strongly increased, thus leaving less assimilates for biomass production. The light extinction coefficient determines the part of incoming radiation that is transmitted by one layer of leaves. An increase in this value implies that less light is transmitted per leaf layer and – as a consequence – that photosynthesis and biomass production.

Finally, as for the sensitivity analysis results of bean yield, it is apparent that none of the parameters has a very strong impact on biomass production. Only two parameters cause changes of more than +10 or –10% in biomass production. Increases of 10% in the values of the top-10 parameters only lead to an average 4% increase in biomass production.

5.5 Concluding remarks

How to interpret the results of this sensitivity analysis? Two important considerations for the interpretation of the results are mentioned below. Firstly, in this sensitivity analysis all input parameters have been changed by 10%. For some input parameters a change of 10% is likely to happen as they are highly variable. However, other input parameters may be much less variable and thus unlikely to change by 10%. Thus, a 10% change is not equally likely to occur in all parameters. Ideally, the changes applied to an input parameter should depend on the degree of variation in that parameter. In other words, it should be scaled to the variation or standard error of the parameter. However, as information on the variation is lacking for almost all parameters, this is not possible. For the interpretation of the results of the sensitivity analysis, this implies that one cannot simply state that breeding of cacao should focus on the highest ranked plant characteristics shown in Figure 5.1 and Table 5.1 (fraction of beans per pod, the maximum rate of photosynthesis, etc.). Whether these highly ranked parameters are a useful focus for breeding depends on their natural variation among individual cacao trees and between varieties. (Note that it furthermore depends on the extent to which variation in these traits is inherited from one to the next generation.) Thus, the list of parameters in Table 5.1 does not directly determine a research agenda for breeding, but may be a first step in establishing such a research agenda.

Secondly, using a different set of input parameters, the results of the sensitivity analysis would probably be strongly changed. Of the input parameters related to the cropping system (those that can be changed in the model), the factor that probably would change the sensitivity results most is the degree of shading. At high levels of shading (not included in this sensitivity analysis), radiation, light interception and efficiency of photosynthesis would probably be much more important in determining bean yield and biomass production than in the lightly shaded situation that was used now. This implies that the gap between simulated or experimental yields on the one hand (see Figure 4.1) and the world average production per ha (around 450 kg ha^{-1} according to FAO data, Krug & Quartey-Papafio 1964) on the other cannot be explained by the parameters that are the most important according to this sensitivity analysis. Certainly, a model for an average cocoa plot of a West African farmer would reveal a different ranking of parameters.

Three conclusions may be drawn on the basis of the results of the sensitivity analysis:

(1) Both the optimisation of the harvestable component as well as the maximisation of the photosynthetic production are of importance for bean production. The first factor includes aspects of investment in pods, fraction of beans per pod and the rate of pod ripening. Equally important is the optimisation of the interception and use of light for the production of assimilates. The key parameters here are the initial light use efficiency and the maximum rate of photosynthesis. It should be noted that especially for the maximum photosynthesis rate, there exists a large variation in the values reported in studies on cacao trees. For the parameterisation of CASE2, the highest value based on a methodologically sound study was chosen (Miyaji *et al.* 1997b).

(2) There is little difference in results of the sensitivity analysis between two countries with considerable differences in climate. In spite of the 40% lower radiation and 25% lower rain fall in Ghana, 9 out of 10 most important parameters are the same for both countries. This implies that factors related to the physiology and morphology of the plant are the most important determinants for yield and productivity. However, it remains to be seen whether this strong

correspondence in results will also be found for different cropping systems (e.g. moderate compared to light shading).

(3) In general the sensitivities found in this analysis are low. That is, there are only few input parameters that (after being changed by 10%) cause the bean yield or biomass production to vary by more than 10%. This is related to the complexity of the model: there are many steps to get from input to output, and in part of these steps other parameters are also involved that may reduce the effect of a change in the input parameter. The consistent low sensitivities also suggest that the model is rather robust. That is, it does not produce disproportionally large – unexpected or unrealistic – changes in output when changing input parameters.

6. Scenarios

6.1 Purpose

The purpose of the scenarios presented in this Chapter is to compare simulated growth and yield of cacao trees under very different circumstances. Scenario studies provide an answer to the question ”What would the growth and production in cocoa plantations be if cocoa were grown in a certain location, on a certain soil type or applying a certain cropping system?”. The main difference with the sensitivity analysis is that (1) changes in input values in different scenarios are much larger than the 10% changes applied in sensitivity analysis; (2) scenarios may be carried by changing several parameters at the same time, whereas in sensitivity typically one parameter is changed at a time; and (3) scenarios are not carried out for all input parameters, whereas in sensitivity analysis all relevant parameters are changed.

6.2 Approach

The approach followed for the scenario studies is as follows. First, a scenario study was carried out for 18 sites in 8 countries for which daily or monthly weather data were available (see Section 6.3.1 for more information on these sites). Secondly, a similar scenario study was carried out for an additional 19 locations in 7 countries for which long-term average weather data were available (see Section 6.3.** for more information on these sites). These sites are located within or close to cocoa production areas in the top-10 cacao producing countries. In both cases the goal was to assess the impact of different weather conditions on estimated growth and yield in cocoa plantations.
On the basis of the first scenario study (with daily or monthly weather data), three locations were selected for use in subsequent scenario studies. This selection was done to decrease the amount of analyses in the scenario studies. The selection was based on the availability of weather data, the geographical location (with the purpose of selecting one site for each of the three continents where cacao is grown) and differences in climatic conditions. The selected locations were Malaysia (Tawau) with a high level of radiation and well-distributed rain, Ghana (Tafo) with a medium level of radiation and a pronounced dry period and Costa Rica (La Lola) with a medium level of radiation and ample rain during the entire year. The other scenarios were carried out for these three sites and assessed the influence of different soil types, shade levels, initial tree ages and water limitation on estimated biomass production and yield in cacao plantations.
Simulations for the scenarios were carried out over a 11-year period. Always the most recent years were used for the simulations. The simulation results of the first year were not used. Standard values were used for the parameters that can be changed by the user. The same standard values were used as in Chapter 3 (see Section 3.2).
For all scenario studies, the natural weather conditions were applied. Thus, no irrigation was applied and water-limited yields were calculated. Furthermore, it was assumed that the crop was very well-managed with respect to nutrients (no nutrient shortage), diseases and pests.

6.3 Locations

6.3.1 Available daily and monthly weather data

Table 6.1 contains information on the 22 sites in 8 countries for which suitable climatic information was available. Whether climatic data was suitable depended on (1) the period of years for which climatic data were available for a site (minimally 9 consecutive years of data should be available); (2) the location of the site in a cocoa producing country and within or close to cocoa production areas (taken from Krug & Quartey-Papafio 1964) and (3) the availability of daily or monthly weather data for radiation, temperature, rainfall and vapour pressure (in case of many missing data, the site was not used). For 22 sites these requirements were met, and simulation runs were carried out. For 4 of the 22 sites, the dry period was too long and the model cacao trees died (that is, depleted their reserves). Simulations for the 18 remaining sites are presented in the next Section.

Table 6.1. List of locations for which simulations were carried out using daily or monthly weather data. Start year, end year and period refer to the availability of climatic data. Simulations were carried out for the last 11 (or less) years of the period for which data were available. Nr refers to the location number (program variable name LOCATION). Fig refers to the Figure in which simulation results are shown; a dash (-) means that simulation were carried out but model trees failed to survive due to low water availability. Type refers to the type of weather data for the location: d for daily weather data (CABO weather format) and m for monthly weather data (WOFOST format).

Nr	Country	Location name	Latitude	Longitude	Altitude	Start	End	Period	Type	Fig
			[degr]	[degr]	[m]	year	Year	[y]		
1	Brazil	Maceio (Alagoas)	-9.67	-35.7	64.5	1961	1969	8	d	6.1
2	Costa Rica	El Carmen	10.2	-83.5	15	1974	1991	18	d	6.2
3	Costa Rica	La Lola	10.1	-83.4	40	1973	1990	18	d	6.3
4	Costa Rica	La Mola	10.4	-83.8	70	1980	1991	12	d	6.4
5	Costa Rica	Puerto Limon	10	-83.1	3	1970	1990	21	d	6.5
6	Ghana	Tafo	6.25	-0.4	200	1963	1997	35	m	6.6
7	Indonesia	Bah Lias	3.16	99.3	30	1979	1993	15	m	6.7
8	Ivory Coast	Abidjan	5.25	-3.93	6	1987	1996	10	m	6.8
9	Ivory Coast	Adiake	5.3	-3.3	39	1987	1995	9	m	6.9
	Ivory Coast	Bondoukou	8.5	-2.78	371	1987	1996	10	m	-
10	Ivory Coast	Daloa	6.87	-6.4	277	1987	1996	10	m	6.10
11	Ivory Coast	Dimbokro	6.65	-4.7	92	1987	1996	10	m	6.11
12	Ivory Coast	Gagnoa	6.13	-5.95	214	1986	1997	12	m	6.12
13	Ivory Coast	Man	7.38	-7.52	340	1987	1996	10	m	6.13
14	Ivory Coast	San Pedro	4.75	-6.6	30	1987	1996	10	m	6.14
	Ivory Coast	Sasandra	4.95	-6.08	62	1987	1996	10	m	-
	Ivory Coast	Yamoussoukro	6.9	-5.3	213	1987	1995	9	m	-
15	Malaysia	Tawau (Sabah)	5.0	117.9	150	1951	1993	43	m	6.15
16	Malaysia	Telok Chengai	6.1	100.3	1	1978	1988	11	m	6.16
17	Papua New Guinea	Dami	-5.5	150	5	1970	1991	22	d	6.17
18	Philippines	IRRI wet station site	14.2	121.3	21	1979	1995	17	d	6.18
	Philippines	Batac MMSU	18		18	1976	1995	20	d	-

Both daily and monthly weather information was used for the simulations. In order to assess the influence of using different types of weather data, model output generated with monthly and daily weather data was compared for the IRRI site in the Philippines. The results of this comparison (Appendix II) show that in the case of a climate with sharp dry and rainy seasons, estimates of biomass production and yield may differ 10%, with higher values when using monthly weather information.

6.3.2 Simulation results per location

Simulation results for the 18 locations shown in Table 6.1 are provided in Figures 6.1-6.18, in the order in which they appear in the Table. A general explanation on the information shown in the graphs and the interpretation of this information is given here. The figure captions contain specific information for each of the sites. This explanation is followed by a short discussion on the interpretation of the results.

Explanation with Figures

a. This graph shows a climatic diagram for the location, including monthly total rain, average temperature and daily radiation. The values shown are averages over the total period for which weather data were available (see Table 6.1). Weather data for individual years were used for the simulations.

b. This graph shows the simulation results for bean yield (dry, fermented beans; program variable name D10YLDBN) compared with the values of the input parameters rain (D10RAIN) and radiation (D10RDD). All values are 10-day totals (sums taken over a period of 10 days). The parameters are shown for years 2-9 of the simulations.

c. This graph shows the simulation results for leaf area index (LAI, program variable name: LAI(1)) compared with the values of the input parameter rain (D10RAIN). The leaf area index is the number of leaf layers present in the cacao canopy. All values are 10-day totals (sums taken over a period of 10 days).

d. This graph shows the simulation results for the parameters biomass production (program variable name: YGTOT) and standing biomass (WTOT). Biomass production is the summed growth of all organs during one year. Note that this value is the gross biomass production, thus including growth in plant parts of which part is lost due to turn over (e.g. fallen leaves or harvested beans). The standing biomass is the value at the end of the year. All biomass is expressed as dry weight. The parameters are shown for years 2-10 of the simulations.

e. This graph shows the simulation results for the parameter bean yield (dry fermented bean, program variable name: YYLDBN) compared to the input parameters rain (YRAIN) and radiation (YRDD). All values are totals for one year. Thus, these values are the integral (total) over one year of the 10-day values for the same parameter shown in graph b. The parameters are shown for years 2-10 of the simulations.

f. This part of the Figure provides 10-year average values for some additional parameters calculated in the model. Harvest index (Program variable name: YHI) is the ratio between dry weight of harvested beans weight and that of the aboveground part of the plant. The harvest increment (YHINCR) is the ratio of the dry weight of the annual yield and annual total aboveground biomass production (in dry weight). The amount of nutrients removed by harvesting beans (YNLOSS, YPLOSS, YKLOSS) is calculated based on the dry bean yield and on the proportion of N, P and K in dry beans. Butter hardness (YMNBH) is the ratio between saturated and unsaturated fatty acids of harvested cocoa beans, which determines the melting point of cacao butter. It is related to the ambient temperature at the onset of fruit ripening (low temperature causing low butter hardness). A butter hardness of 1.7 is “normal” (Wood &

Lass 1985). The ripening period of the pods (YMNIPOD) depends on the average temperature. A “normal” value for ripening period is 150 days. The latter two parameters are average values weighted for yield.

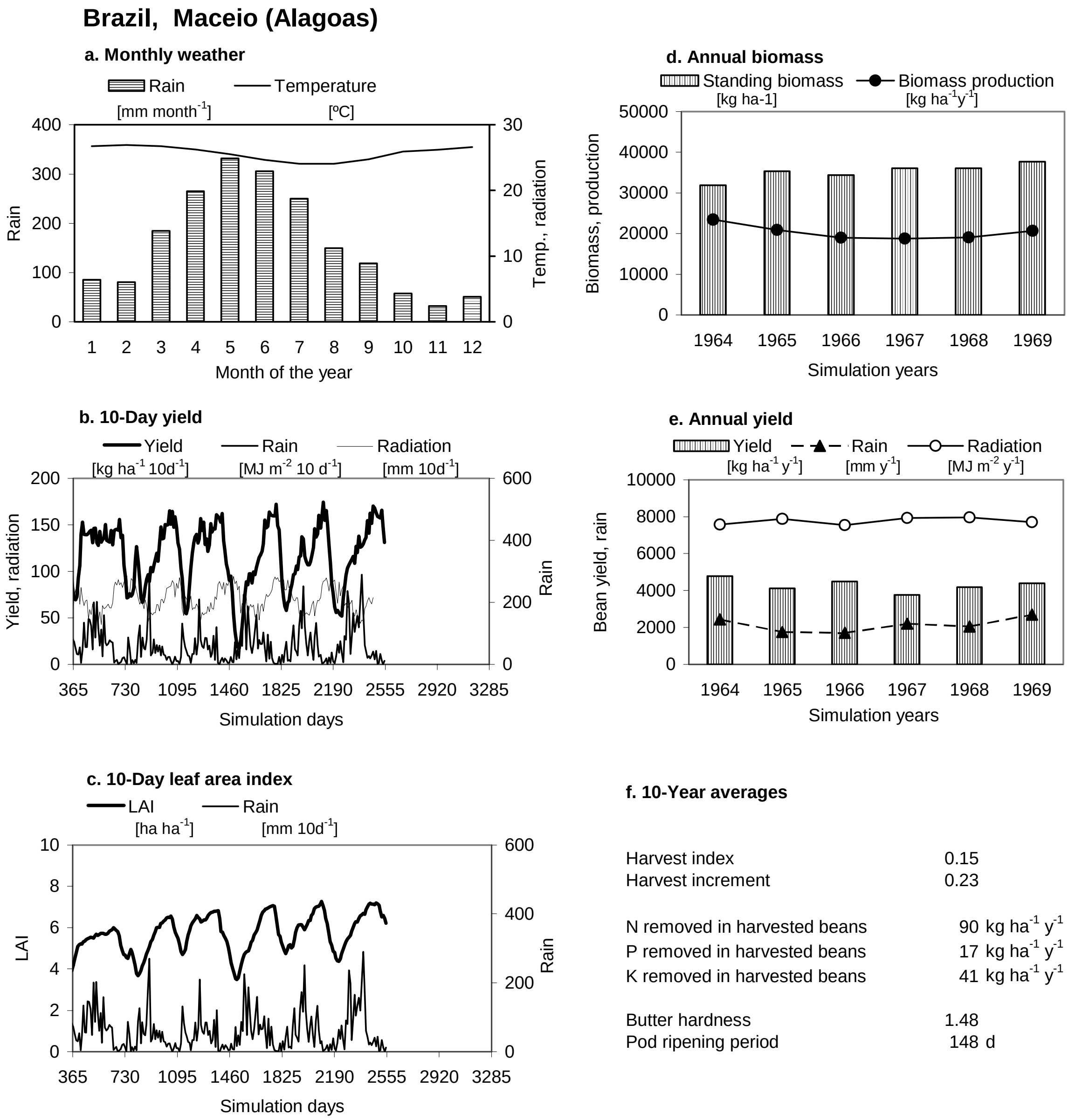
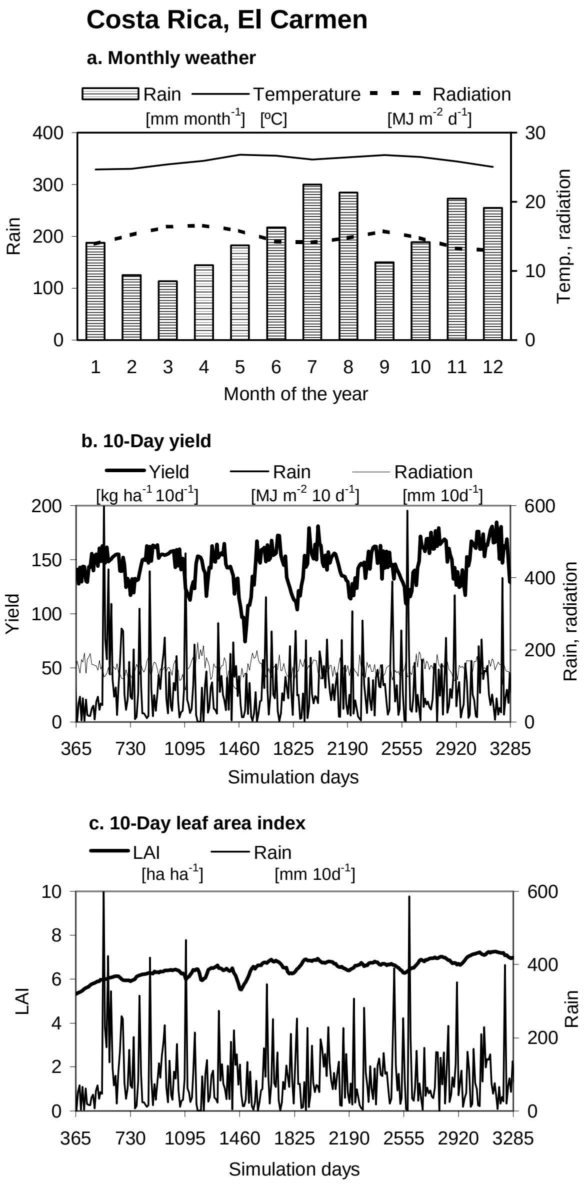
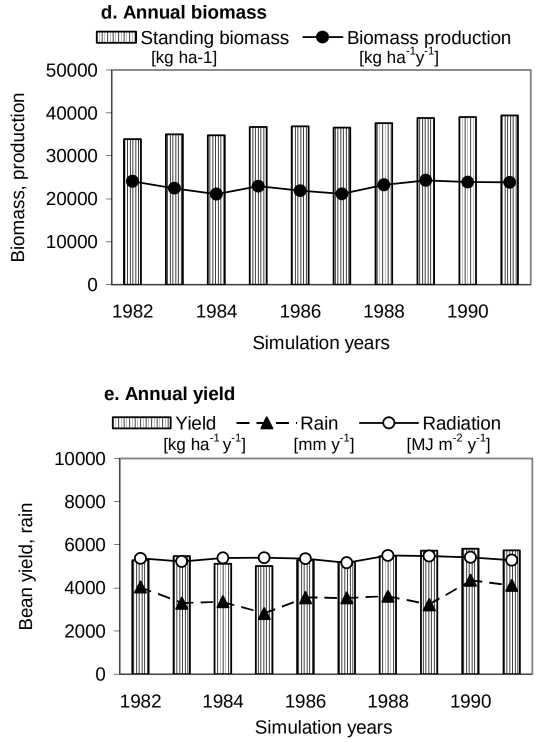


Figure 6.1. Simulation results using climatic data for Maceio (Alagoas) in Brazil. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. For this location, weather data were available for a limited number of years (1961-1969), of which the first two years were very dry, causing the death of the model trees. For the period 1963-1969 cocoa growth and production was simulated without problems. Note that no figures for radiation are given as only information on sun hours was available. In the model this was translated into radiation. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.





f. 10-Year averages

Harvest index	0.18
Harvest increment	0.25
N removed in harvested beans	114 kg ha^{-1} y^{-1}
P removed in harvested beans	22 kg ha^{-1} y^{-1}
K removed in harvested beans	51 kg ha^{-1} y^{-1}
Butter hardness	1.60
Pod ripening period	146 d

Figure 6.2. Simulation results using climatic data for El Carmen in Costa Rica. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

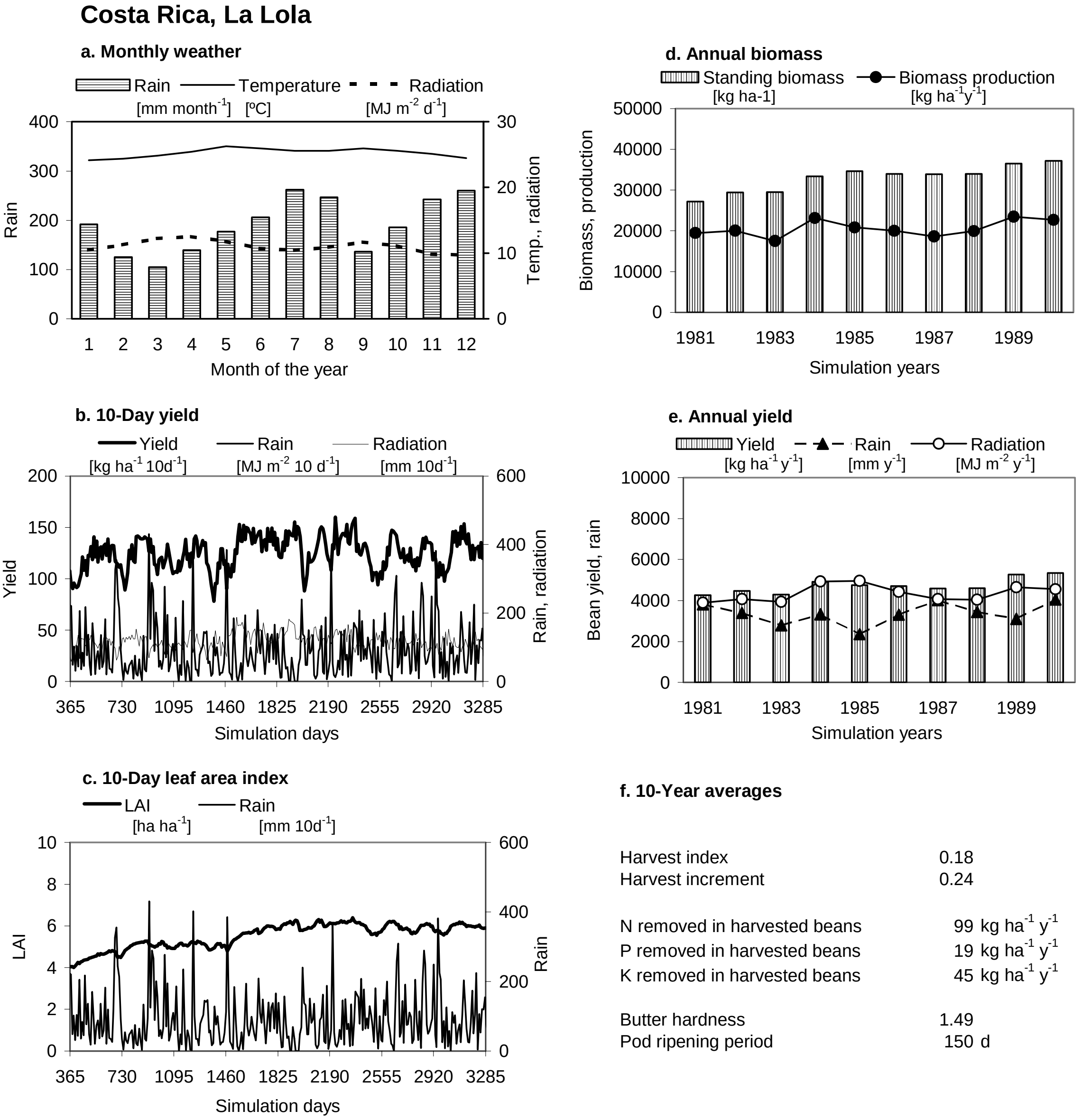
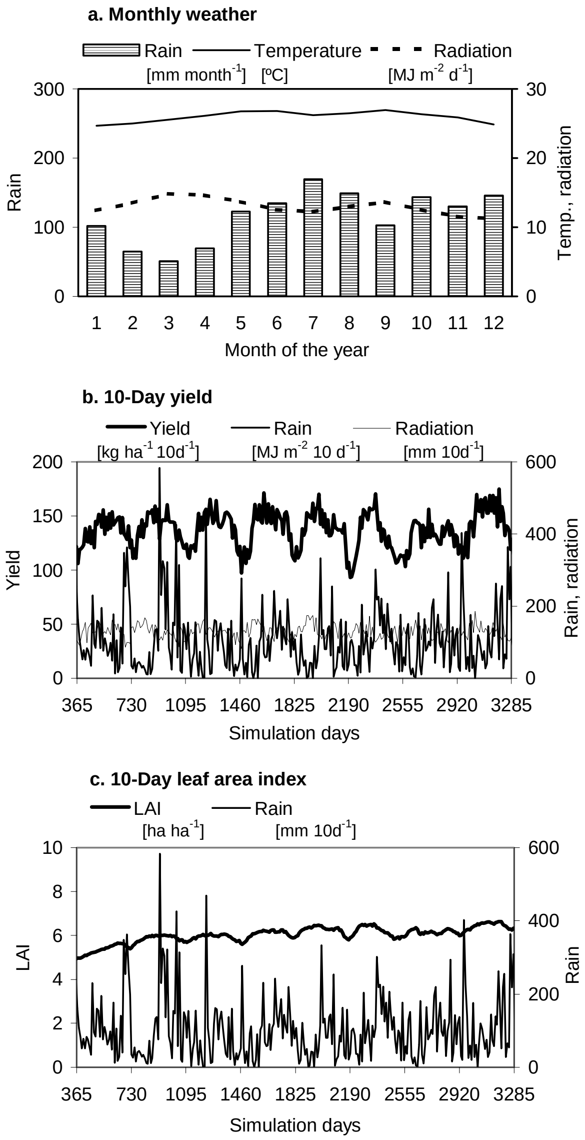
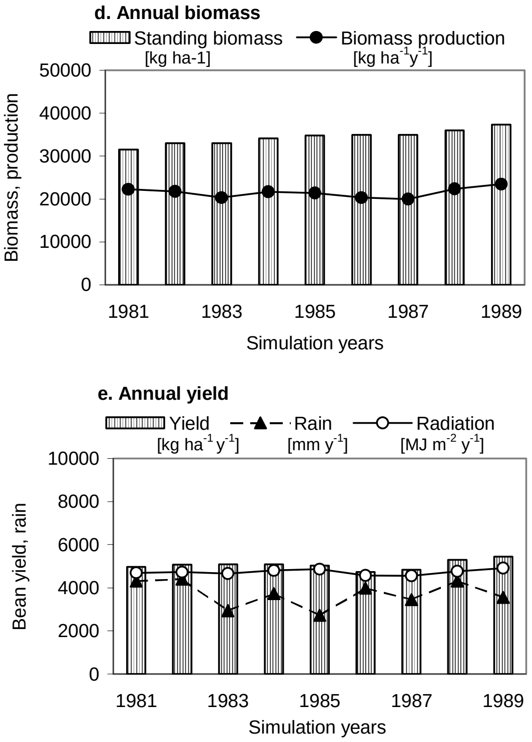


Figure 6.3. Simulation results using climatic data for La Lola in Costa Rica. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

Costa Rica, La Mola





f. 10-Year averages

Harvest index	0.18
Harvest increment	0.25
N removed in harvested beans	106 kg ha^{-1} y^{-1}
P removed in harvested beans	20 kg ha^{-1} y^{-1}
K removed in harvested beans	48 kg ha^{-1} y^{-1}
Butter hardness	1.59
Pod ripening period	147 d

Figure 6.4. Simulation results using climatic data for La Mola in Costa Rica. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

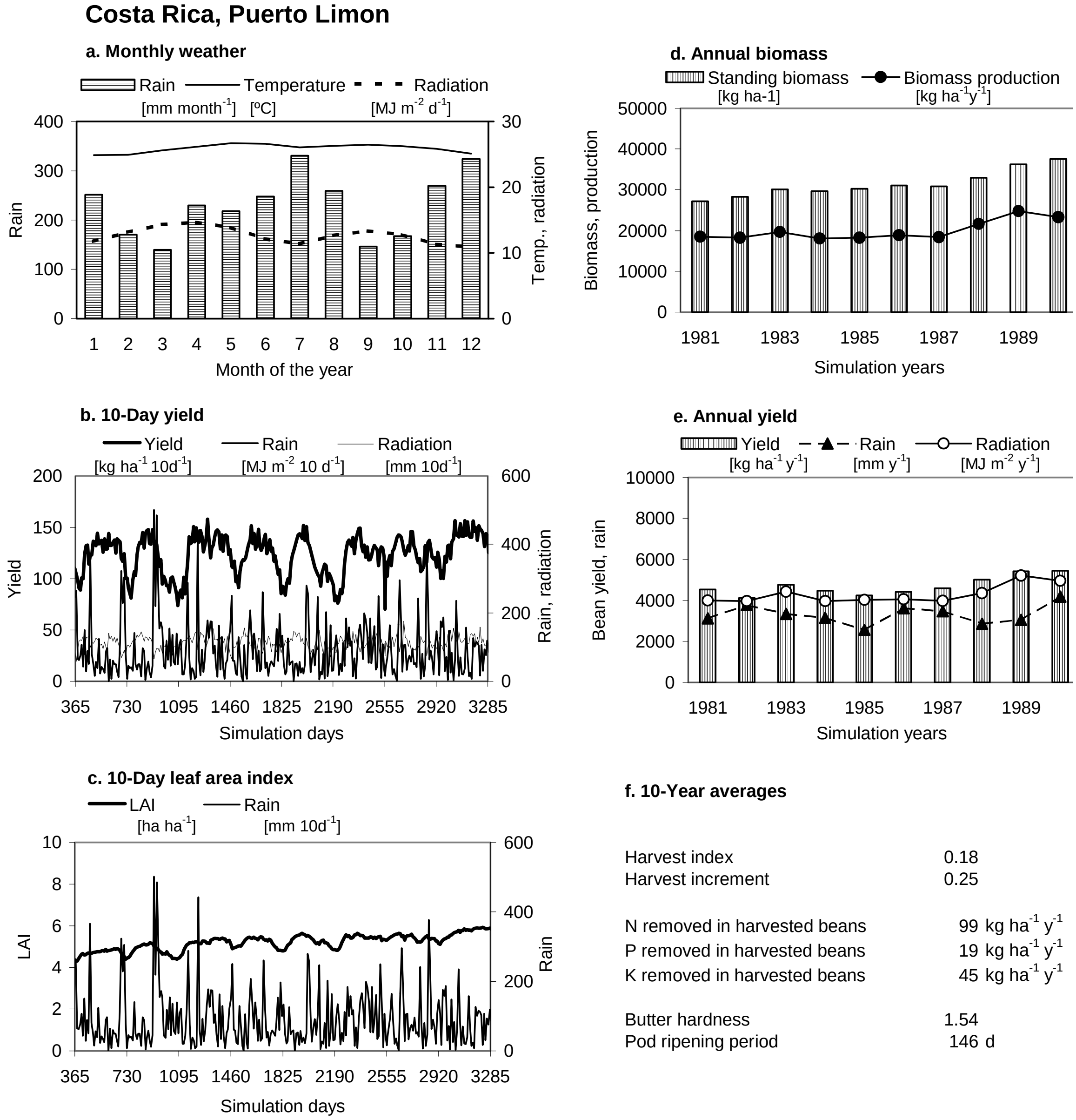


Figure 6.5. Simulation results using climatic data for Puerto Limon in Costa Rica. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

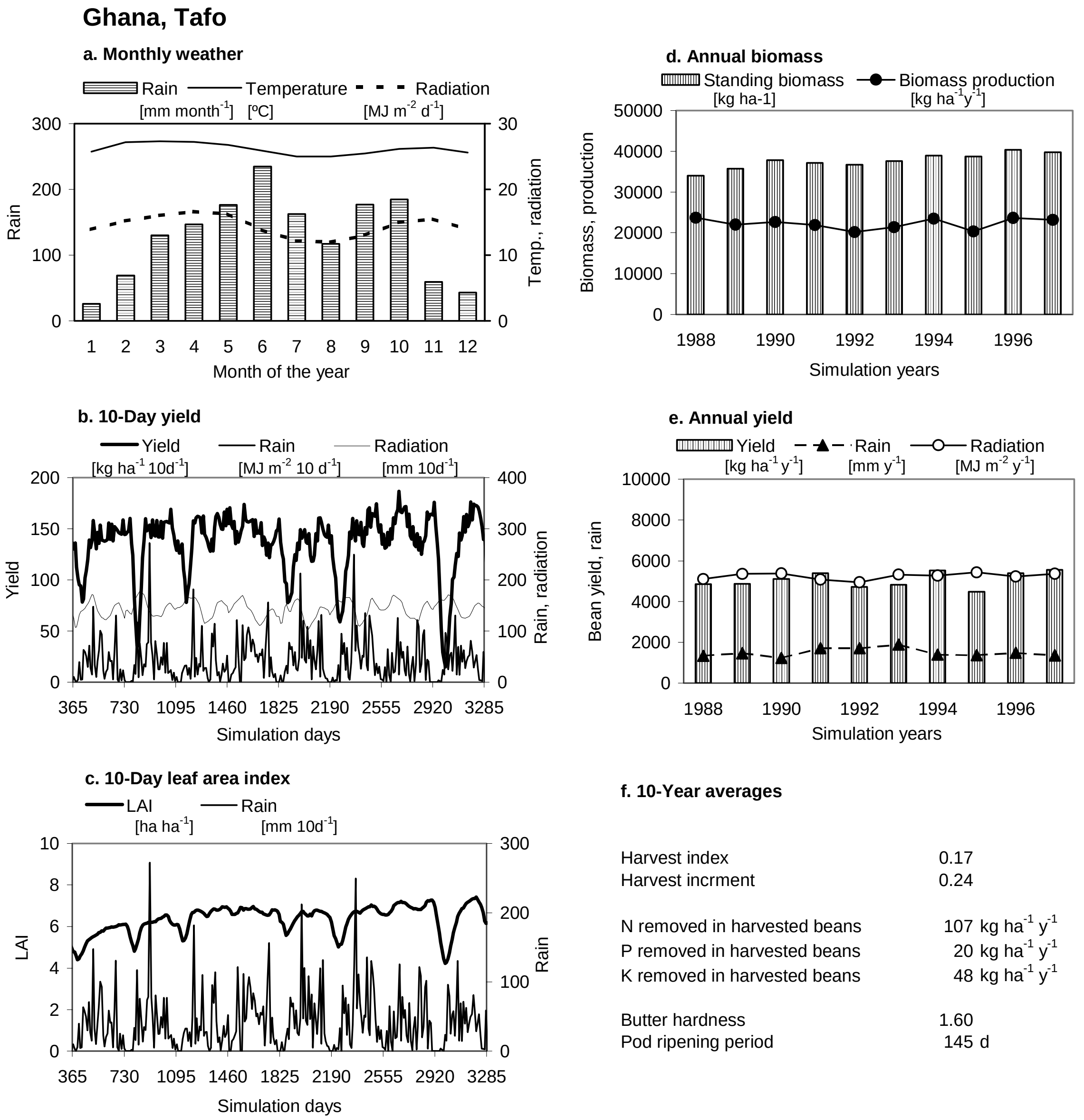
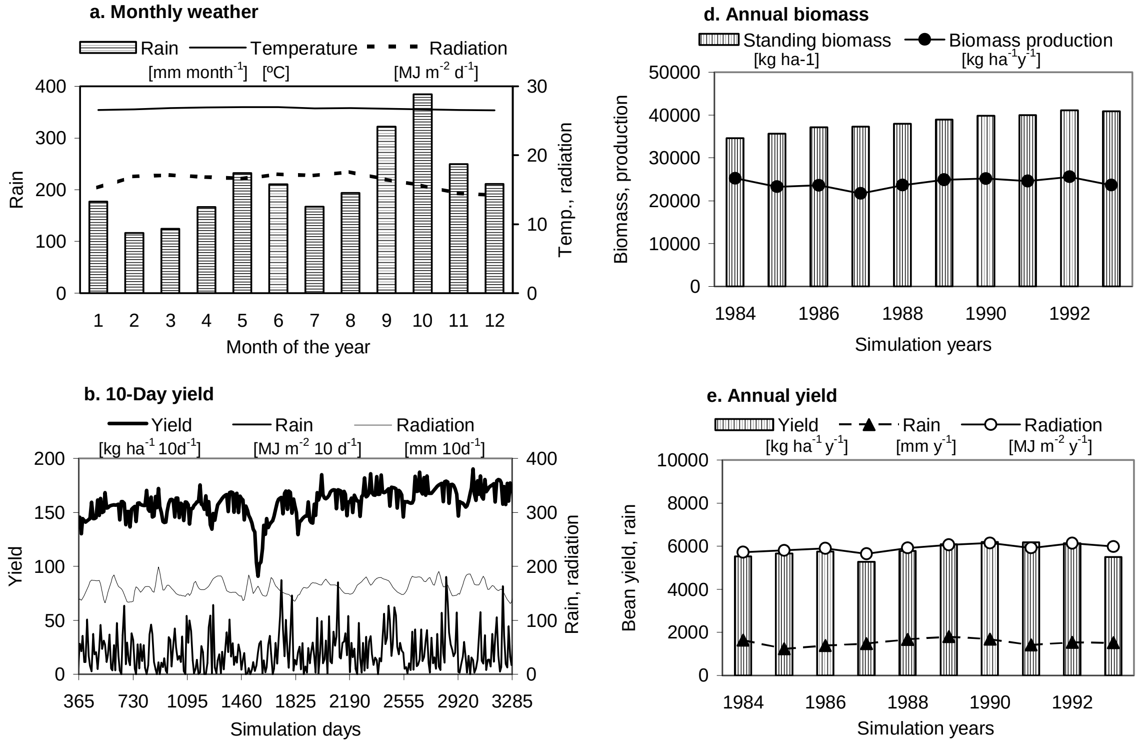
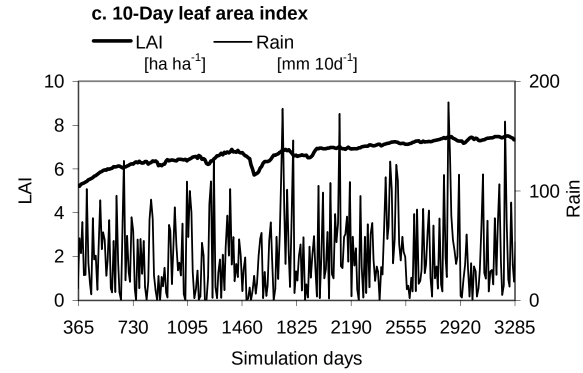


Figure 6.6. Simulation results using climatic data for Tafo in Ghana. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

Indonesia, Bah Lias



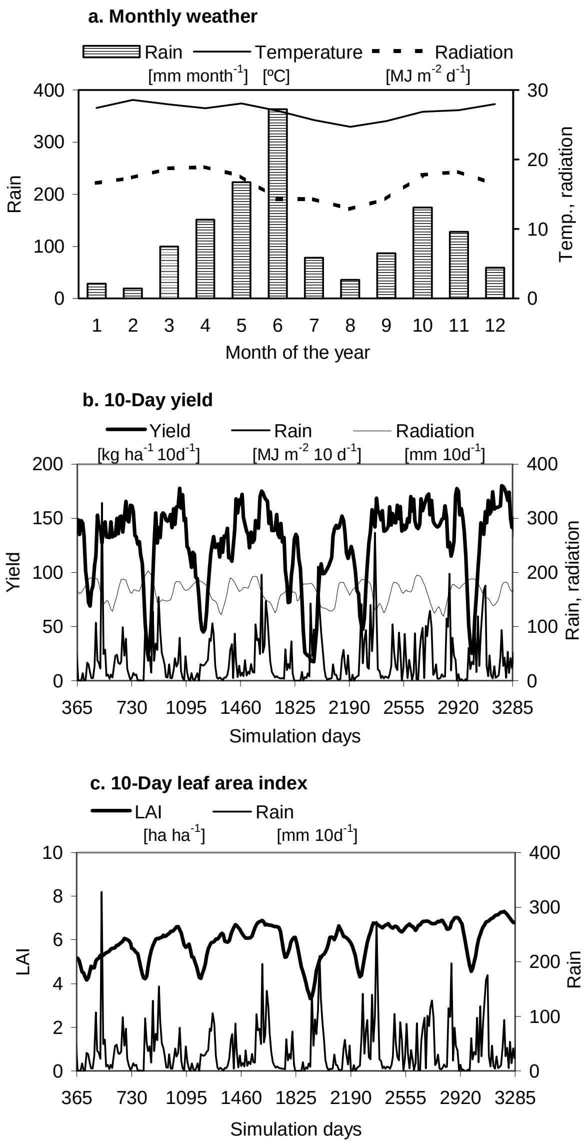


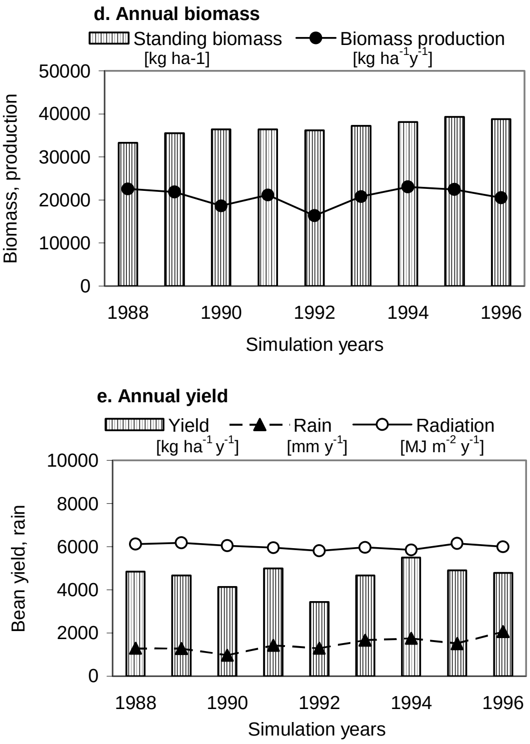
f. 10-Year averages

Harvest index	0.19
Harvest increment	0.25
N removed in harvested beans	122 kg ha^{-1} y^{-1}
P removed in harvested beans	23 kg ha^{-1} y^{-1}
K removed in harvested beans	55 kg ha^{-1} y^{-1}
Butter hardness	1.72
Pod ripening period	141 d

Figure 6.7. Simulation results using climatic data for Bah Lias (Sumatra) in Indonesia. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

Ivory Coast, Abidjan





f. 10-Year averages

Harvest index	0.16
Harvest increment	0.24
N removed in harvested beans	98 kg ha^{-1} y^{-1}
P removed in harvested beans	19 kg ha^{-1} y^{-1}
K removed in harvested beans	44 kg ha^{-1} y^{-1}
Butter hardness	1.63
Pod ripening period	142 d

Figure 6.8. Simulation results using climatic data for Abidjan in Ivory Coast. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

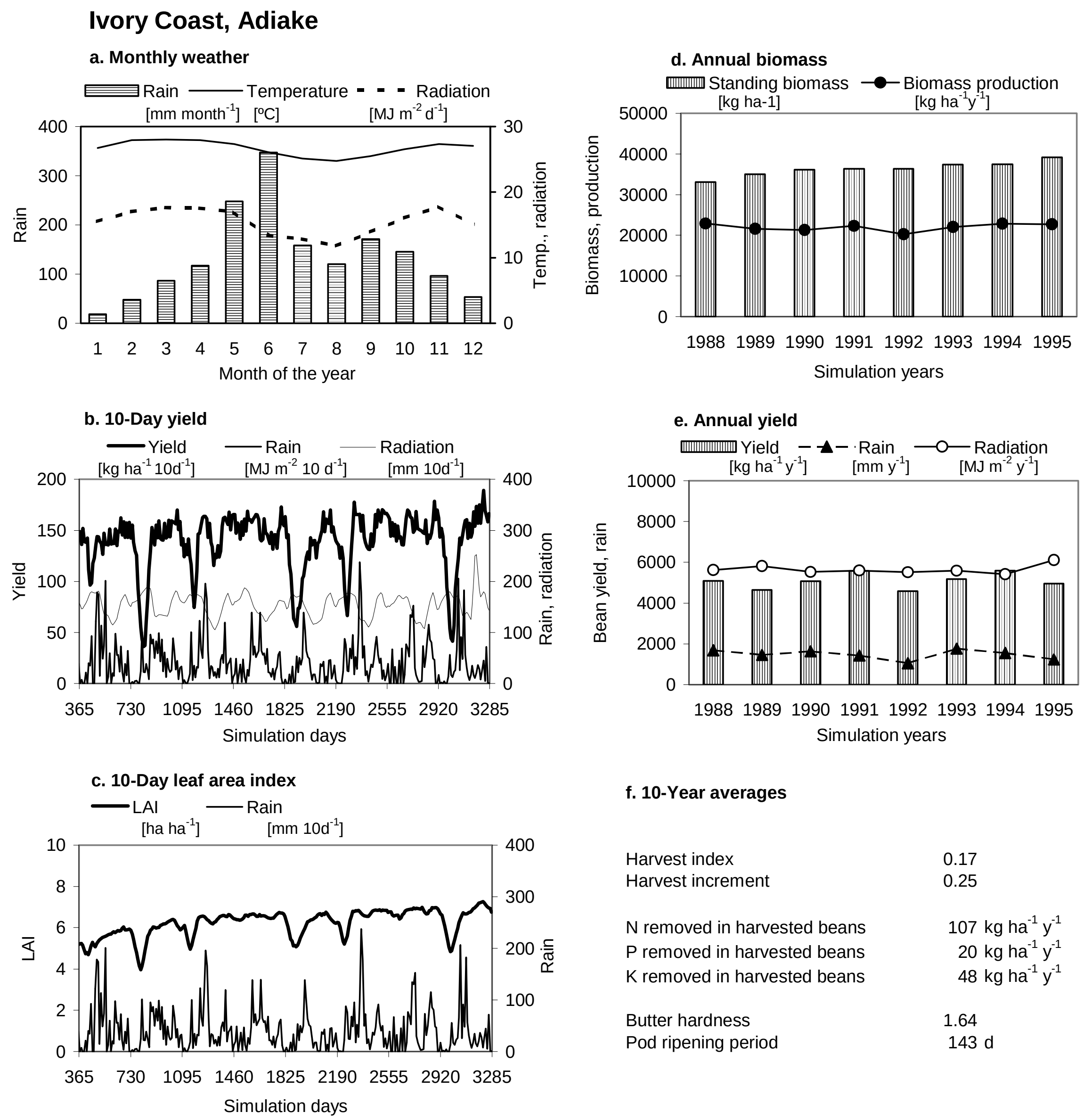


Figure 6.9. Simulation results using climatic data for Adiake in Ivory Coast. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

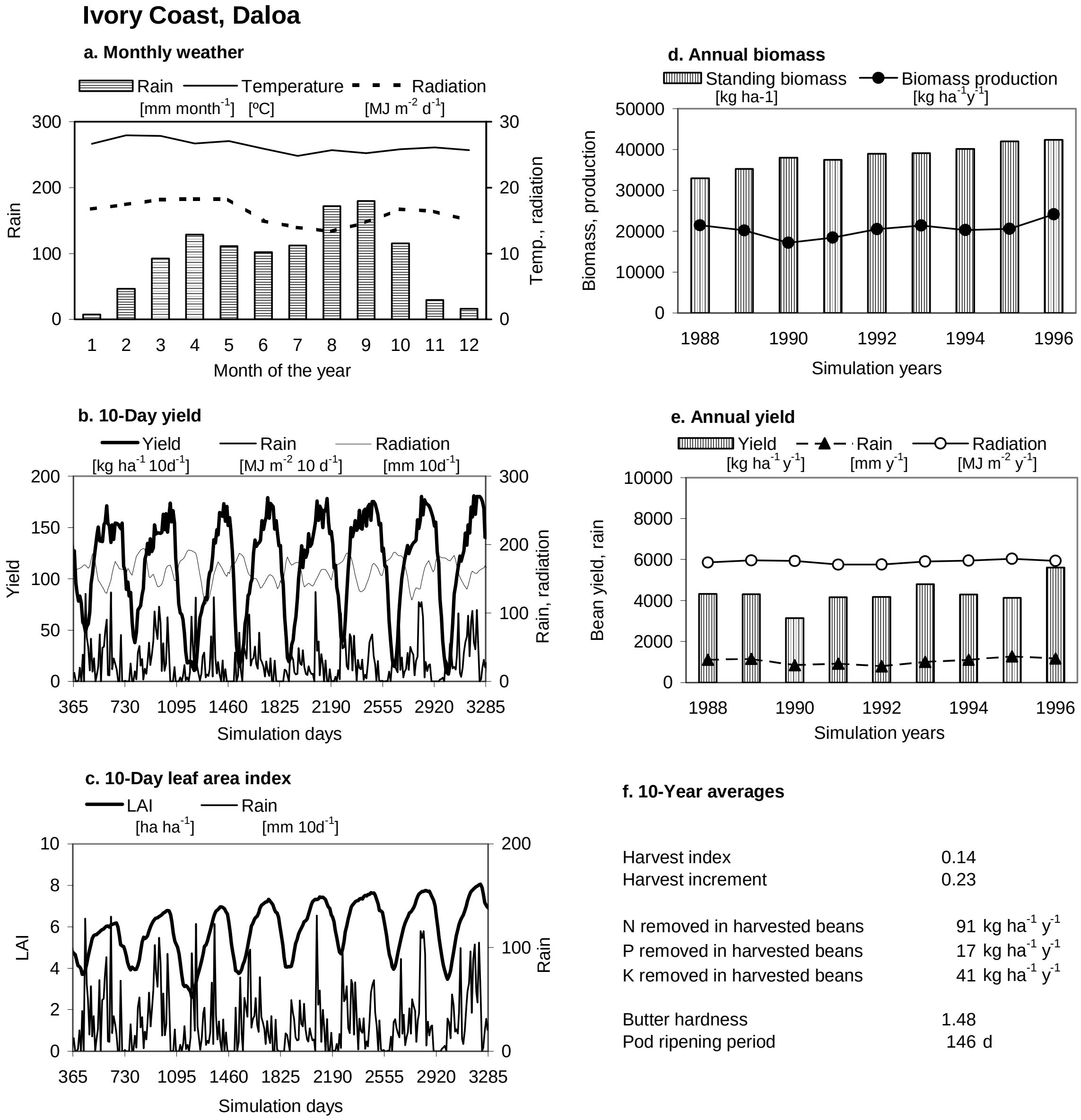
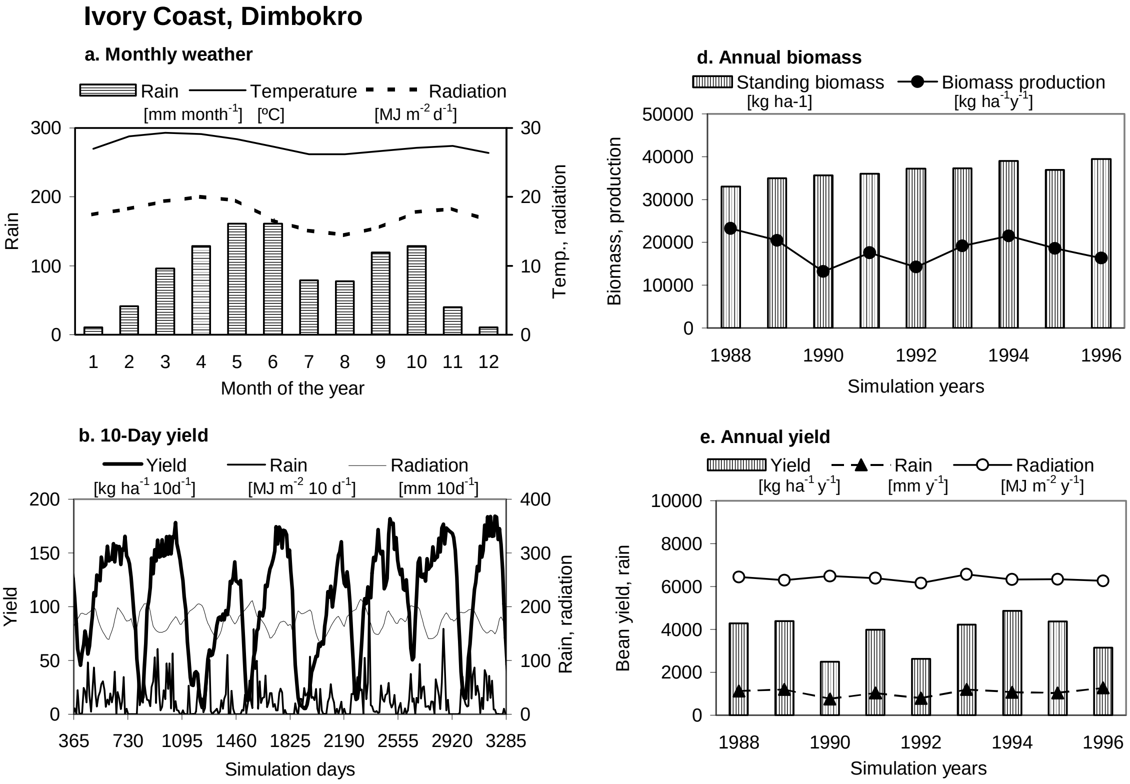
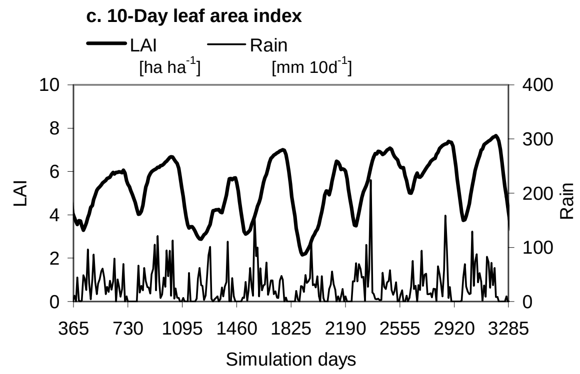


Figure 6.10. Simulation results using climatic data for Daloa in Ivory Coast. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

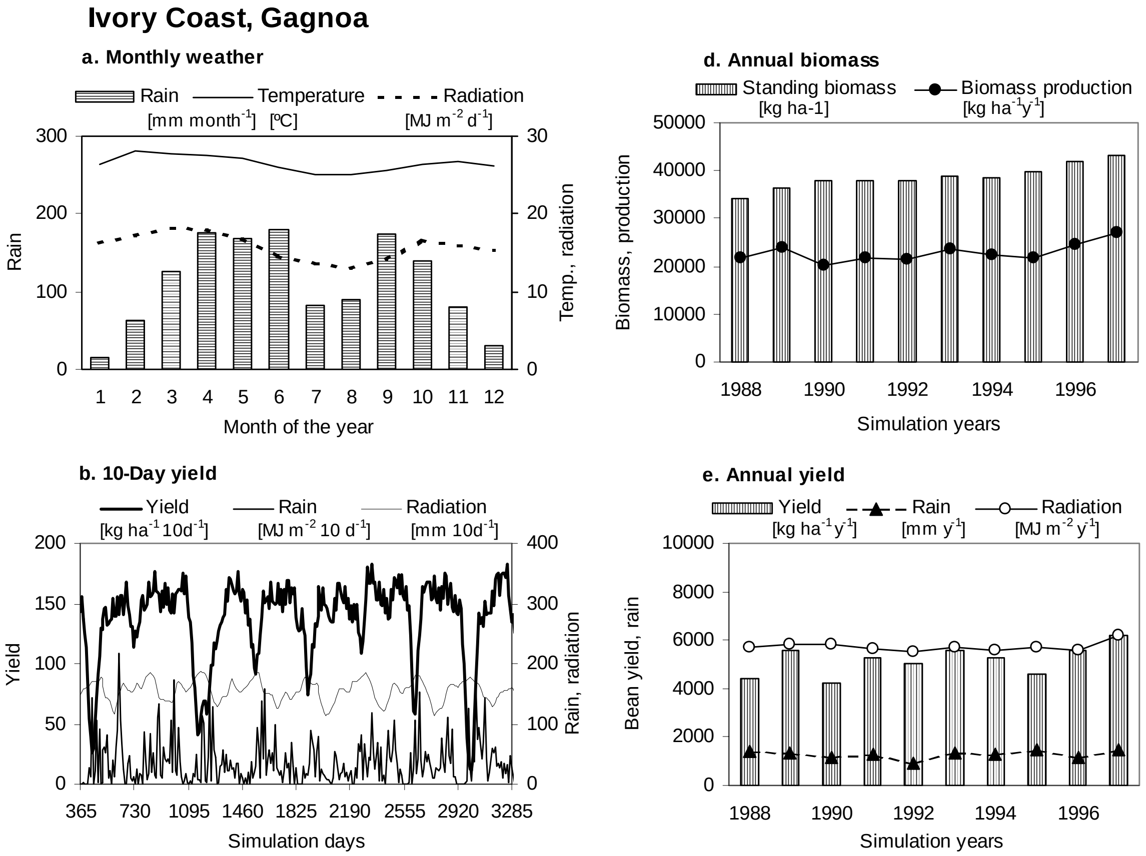


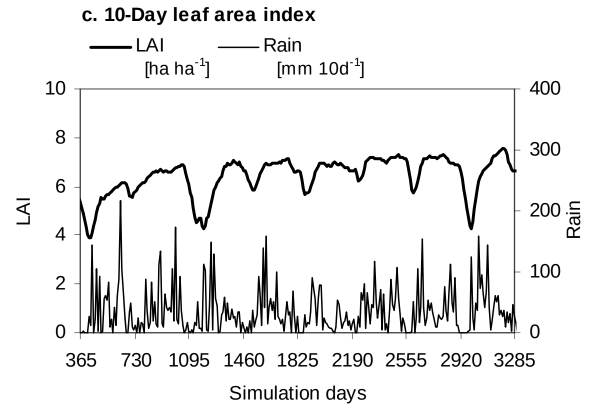


f. 10-Year averages

Harvest index	0.13
Harvest increment	0.22
N removed in harvested beans	80 kg ha^{-1} y^{-1}
P removed in harvested beans	15 kg ha^{-1} y^{-1}
K removed in harvested beans	36 kg ha^{-1} y^{-1}
Butter hardness	1.53
Pod ripening period	141 d

Figure 6.11. Simulation results using climatic data for Dimbokro in Ivory Coast. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.





f. 10-Year averages

Harvest index	0.16
Harvest increment	0.24
N removed in harvested beans	109 kg ha^{-1} y^{-1}
P removed in harvested beans	21 kg ha^{-1} y^{-1}
K removed in harvested beans	49 kg ha^{-1} y^{-1}
Butter hardness	1.59
Pod ripening period	144 d

Figure 6.12. Simulation results using climatic data for Gagnoa in Ivory Coast. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

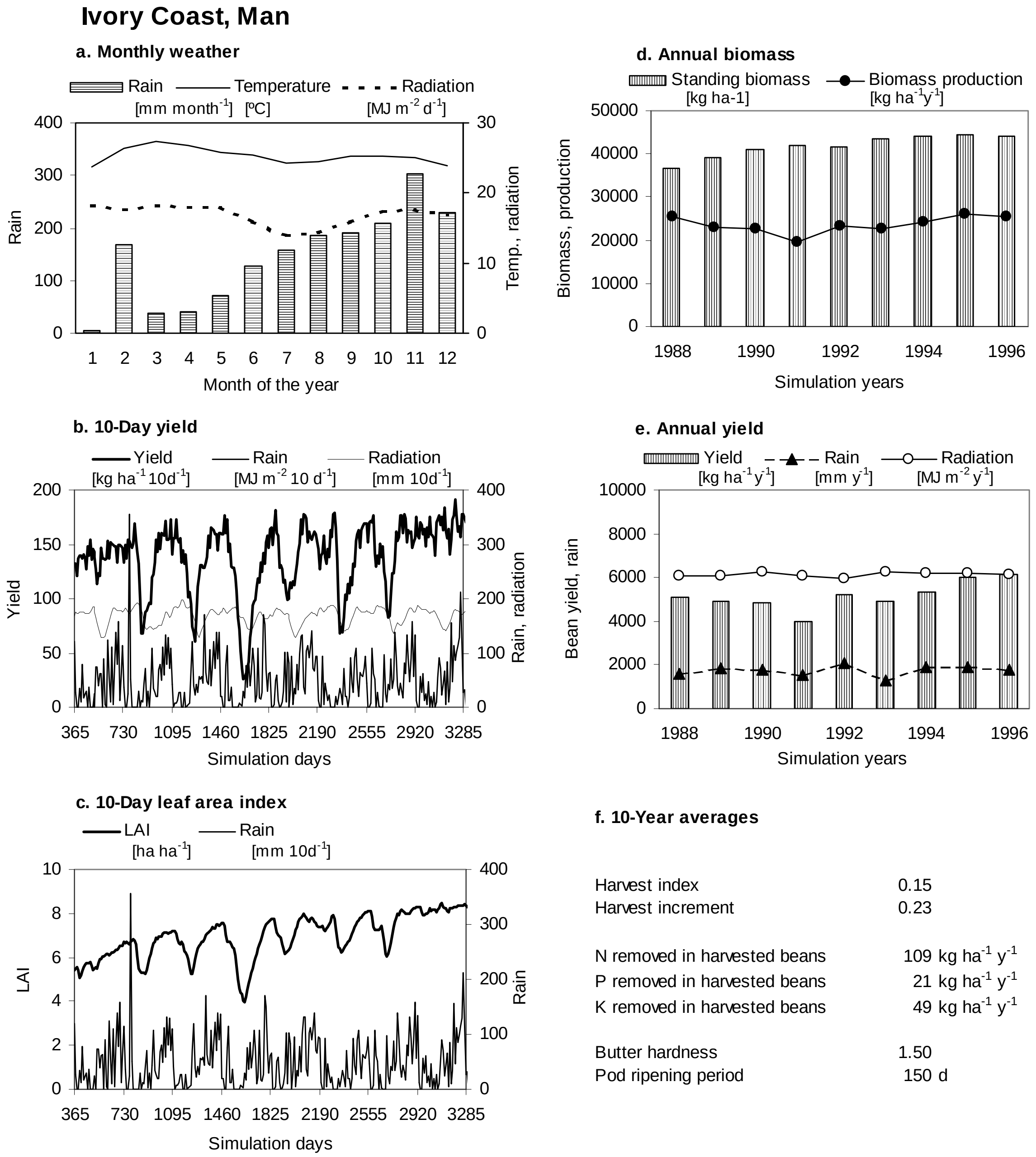


Figure 6.13. Simulation results using climatic data for Man in Ivory Coast. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

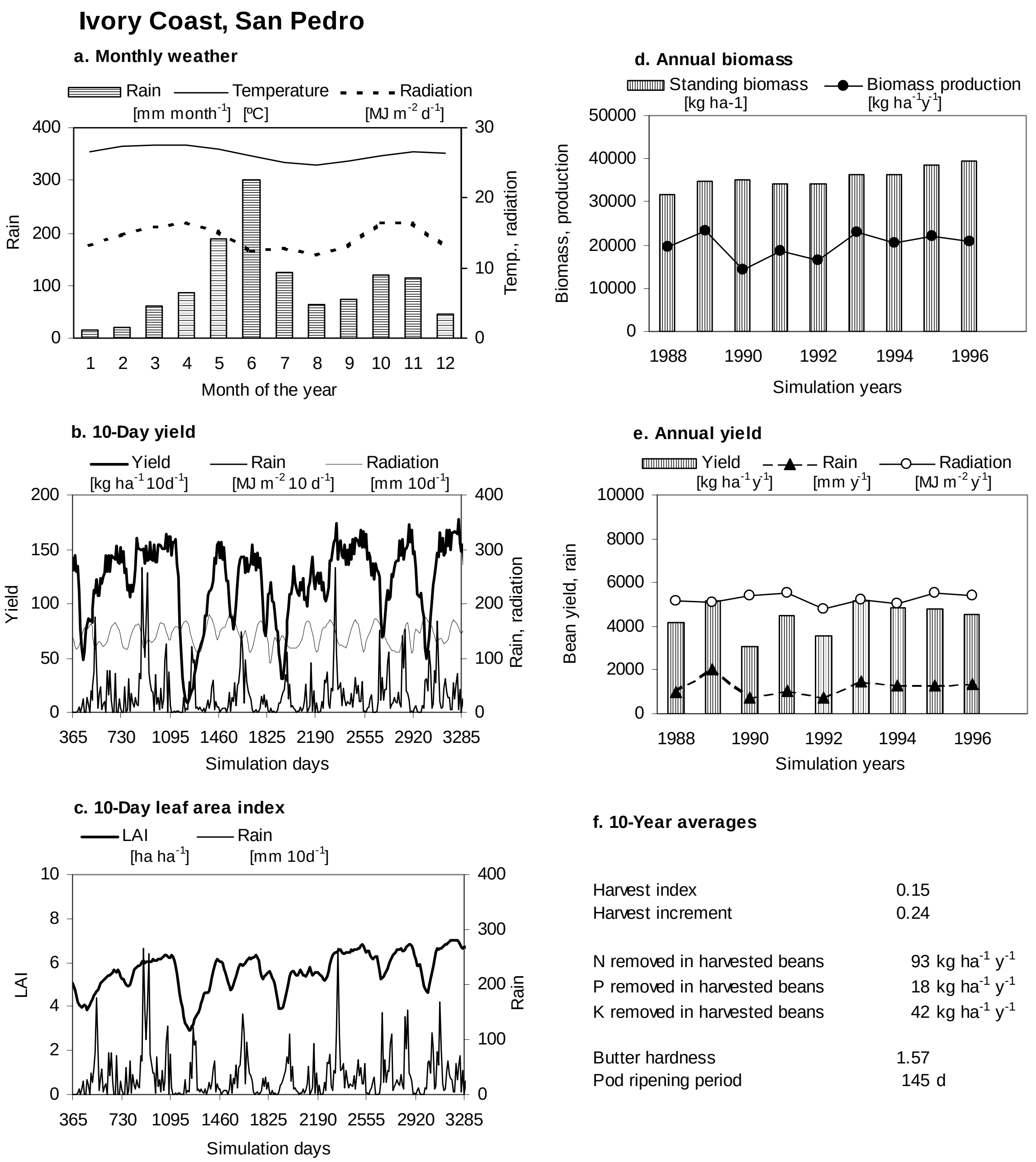
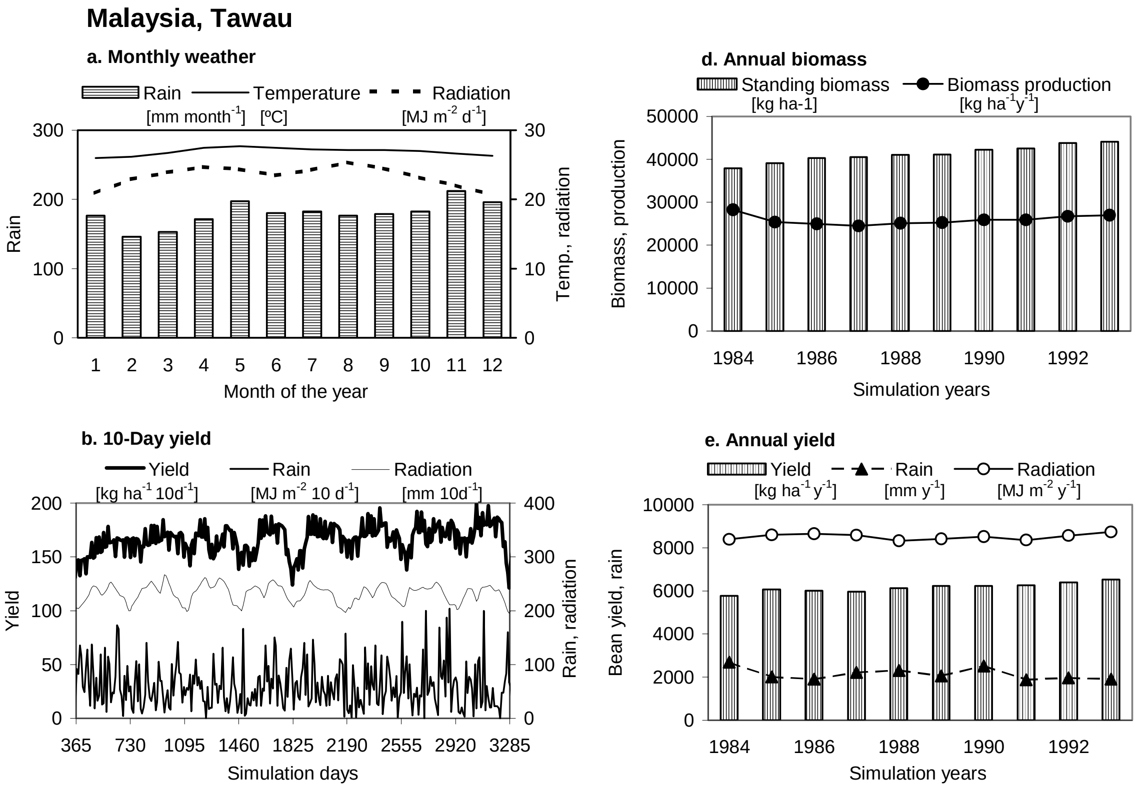
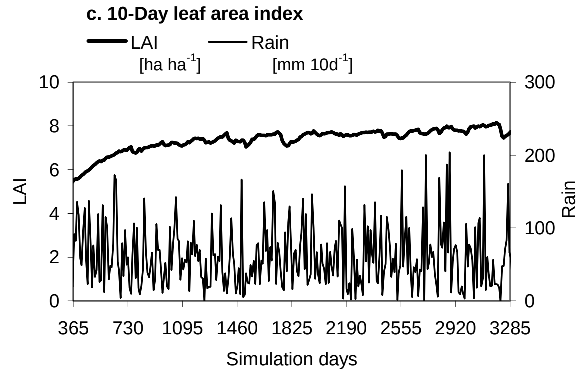


Figure 6.14. Simulation results using climatic data for San Pedro in Ivory Coast. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.





f. 10-Year averages

Harvest index	0.18
Harvest increment	0.25
N removed in harvested beans	129 kg ha^{-1} y^{-1}
P removed in harvested beans	25 kg ha^{-1} y^{-1}
K removed in harvested beans	59 kg ha^{-1} y^{-1}
Butter hardness	1.68
Pod ripening period	142 d

Figure 6.15. Simulation results using climatic data for Tawau (Sabah) in Malaysia. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

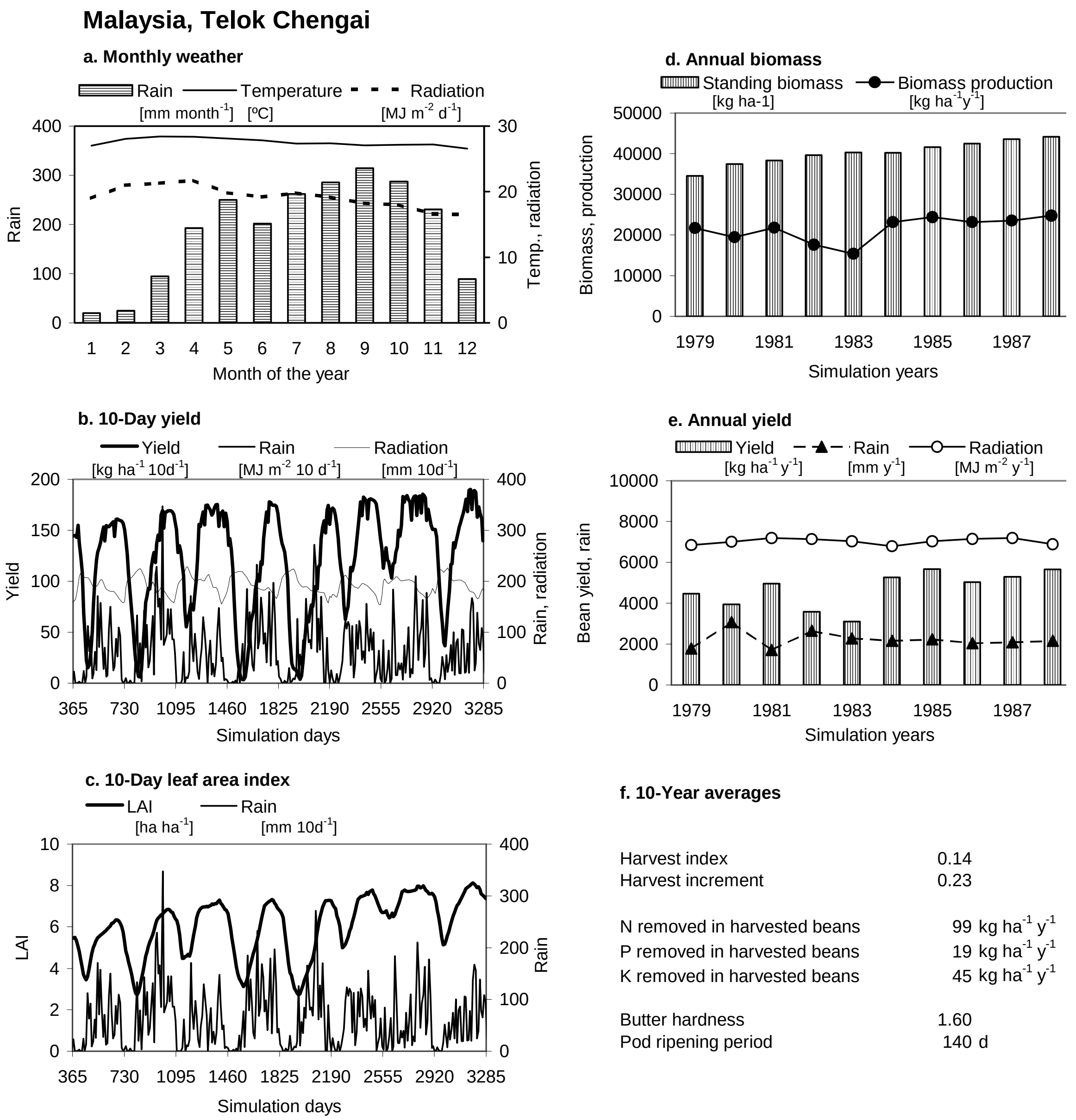


Figure 6.16. Simulation results using climatic data for Telok Chengai in Malaysia. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

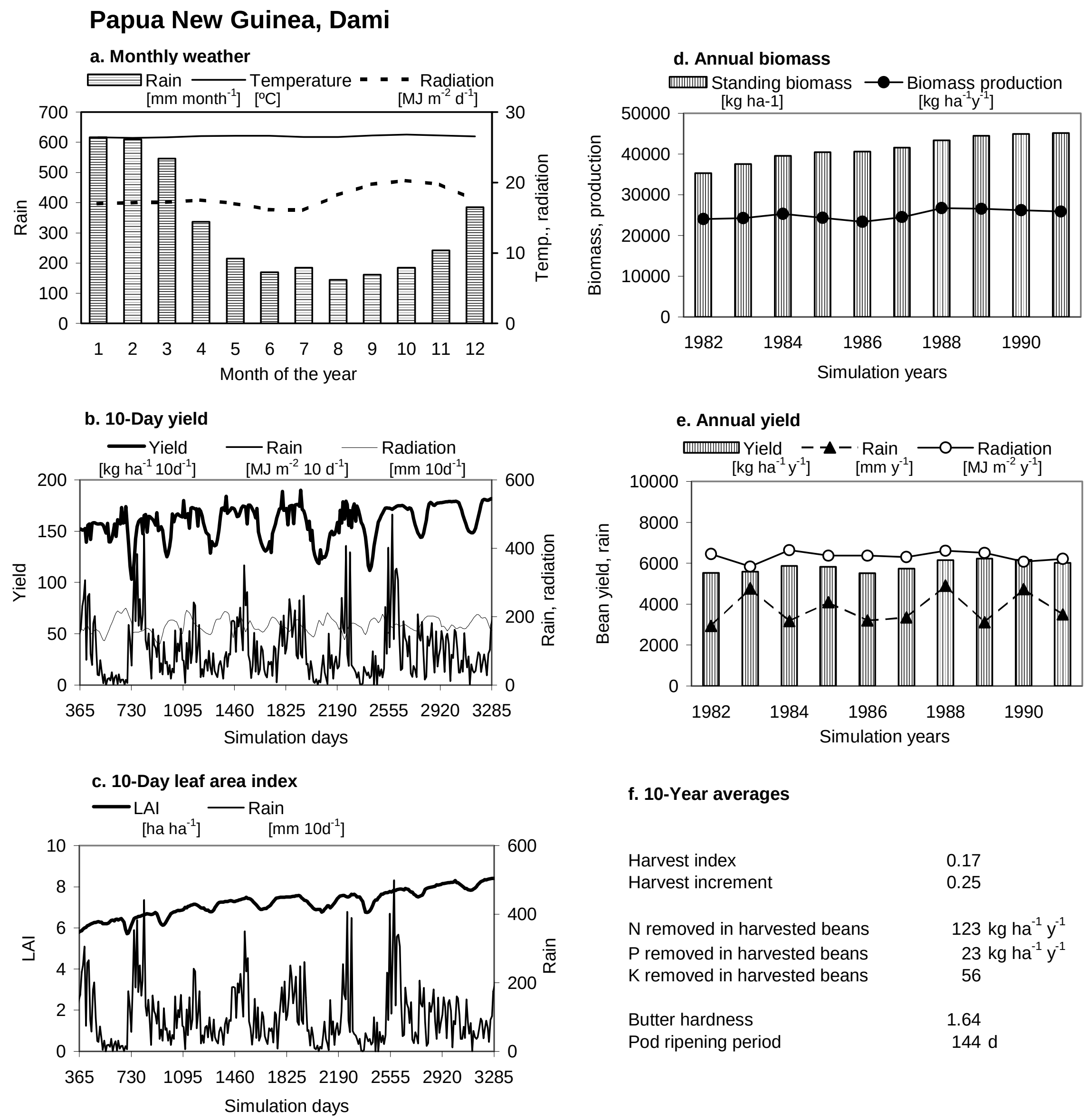
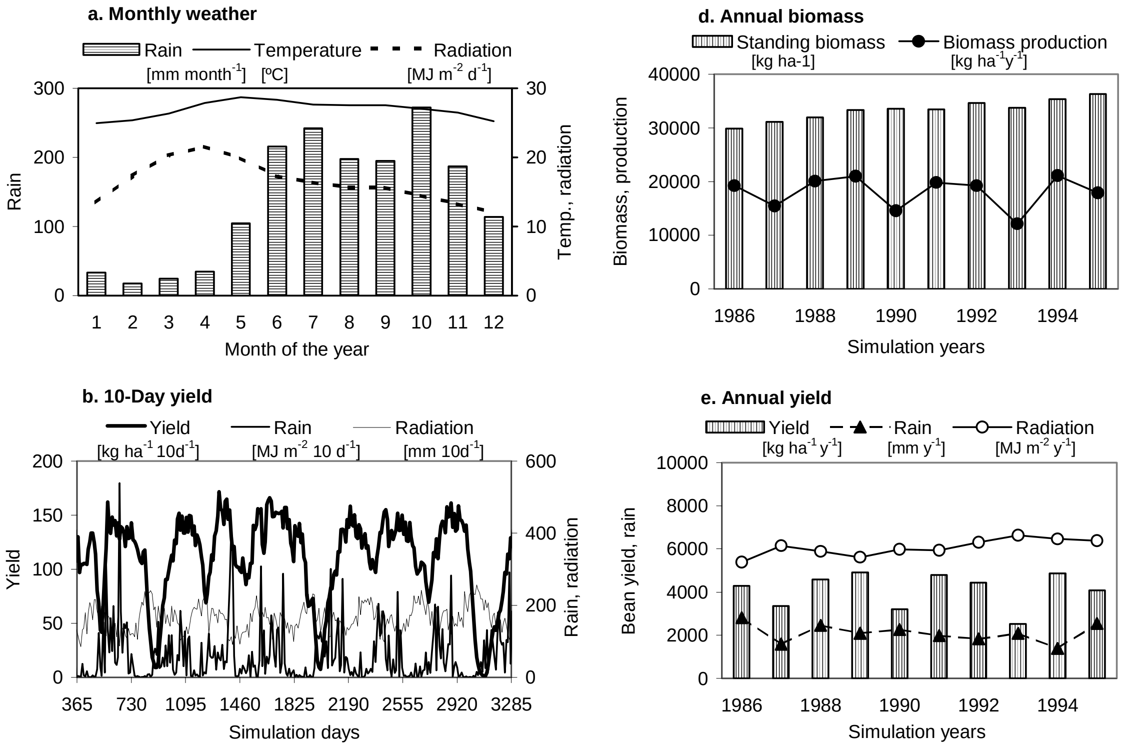
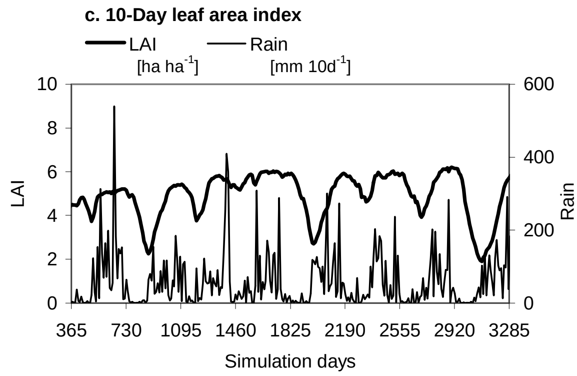


Figure 6.17. Simulation results using climatic data for Dami in Papua New Guinea. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

Philipines, IRRI wet station site





f. 10-Year averages

Harvest index	0.15
Harvest increment	0.24
N removed in harvested beans	86 kg ha^{-1} y^{-1}
P removed in harvested beans	16 kg ha^{-1} y^{-1}
K removed in harvested beans	39 kg ha^{-1} y^{-1}
Butter hardness	1.56
Pod ripening period	142 d

Figure 6.18. Simulation results using climatic data from IRRI in Philippines. General explanation of the different parts of this Figure is provided in Section 6.3.2. Information on the location is given in Table 6.1. The soil type used for these simulations was not specific to this location; one soil type was used for all locations (see Table 3.1 or soil 1 in Table 6.2). Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.

6.3.3 Comparing locations (daily/monthly weather data)

A comparison of the model output for the 18 locations with daily/monthly weather data shows large variation in climatic conditions resulting in a large variation in simulated cocoa growth and yield (Figures 6.1-6.18). When considering the 10-day output, very strong fluctuations in bean yield can be observed for some of the locations. These fluctuations correspond to extended periods with low rainfall. In areas without severe dry seasons, more moderate fluctuations in bean yield are observed (e.g. Tawau, Malaysia: Figure 6.16). In this case, the variation in bean yield is mostly caused by variation in radiation. Low bean yield due to reduced water availability is caused by reduced photosynthetic activity in periods of water stress, as well as by a decrease in the amount of leaves (measured by the leaf area index, the number of leaf layers in the canopy per m^2 soil). The latter can be seen in graphs (c) of the 18 scenario Figures. At locations with a severe dry season, the leaf area index drops sharply during periods of water shortage. These dips in leaf area are caused by an increased leaf loss and a reduced leaf production.
Looking at graphs (e) in Figures 6.1-6.18 with annual yield, considerable fluctuations can be observed for locations with a pronounced dry season. If these fluctuations are compared to the variation in annual rain fall, there appears to be no correlation between yield and rain. That is, years with low annual rainfall are not necessarily those with a low bean yield, and vice versa. This is related to the fact that reductions in bean yield are due to the *distribution* of rain fall over the year rather than to the total *amount* of rain per year. This is clearly illustrated by comparing the 10-day graphs (b) on bean yield with the annual graphs (e): when strong dips in yield occur in the 10-day graphs, they correspond to a low annual production in the annual graph, but not necessarily with a low annual rainfall. Annual rainfall therefore seems to be a poor indicator for yield (for one location).
Comparing biomass production and bean yield in the annual graphs (d and e) in Figures 6.1-6.18 reveals a good correlation between the two. This can be understood as pod growth (and thus the yield of pod and beans) is part of total biomass growth.
The values mentioned under the heading “f” in Figures 6.1-6.18 are 10-year averages for harvest-related parameters. Especially of importance is the amount of nutrients removed from the cocoa plantation due to the harvesting of beans. These values may be considerable, with an average removal of 100 kg N, 20 kg P and 45 kg K per ha and per year. Highest values for nutrient removal (in the case of Malaysia, Tawau in Figure 6.15) are 129, 25 and 59 kg ha^{-1} y^{-1} respectively. The values of the two harvest indices (harvest index and harvest increment) show that the dry weight of the annual bean yield amounts to an average 16% of the total aboveground dry weight (HI, Harvest Index; average over all locations). When expressed as a percentage of the total biomass production (HIncr, Harvest increment) this value is higher, on average 24%. Values for HI vary between 13 and 19% (in Figure 6.11 and 6.7, respectively). A large part of this variation can be attributed to variation in annual rainfall: harvest index values increase with a higher annual precipitation. The same trend is found for harvest increment (HIncr).

Figure 6.19 summarises the results of the scenario study for 18 locations. Between locations, a large variation in yield can be observed. Comparing yield figures with annual rain and radiation does not show a clear relation: locations with high radiation do not necessarily reach higher simulated bean yield than those with low radiation; the same is true for rainfall. It is clear that both factors play a role, and that – as described above – the distribution of rain over the year is of importance for bean yield. The pattern of leaf area index (LAI) values corresponds closely to that of bean yield (compare parts a and c of Figure 6.19). Locations for which low LAI values are simulated generally have low bean yield and high LAI values correspond to high yield. Again, there is no clear relation between LAI on the one hand and rain or radiation on the other. The production of biomass and the average amount of standing biomass (both in terms of dry weight) show less variation than LAI or bean yield, but the pattern of variation between locations is comparable. Finally, butter hardness and average ripening period for pods varies among sites according to temperature. Butter hardness varies between 1.48 and 1.72; ripening period between 140 and 150 days.

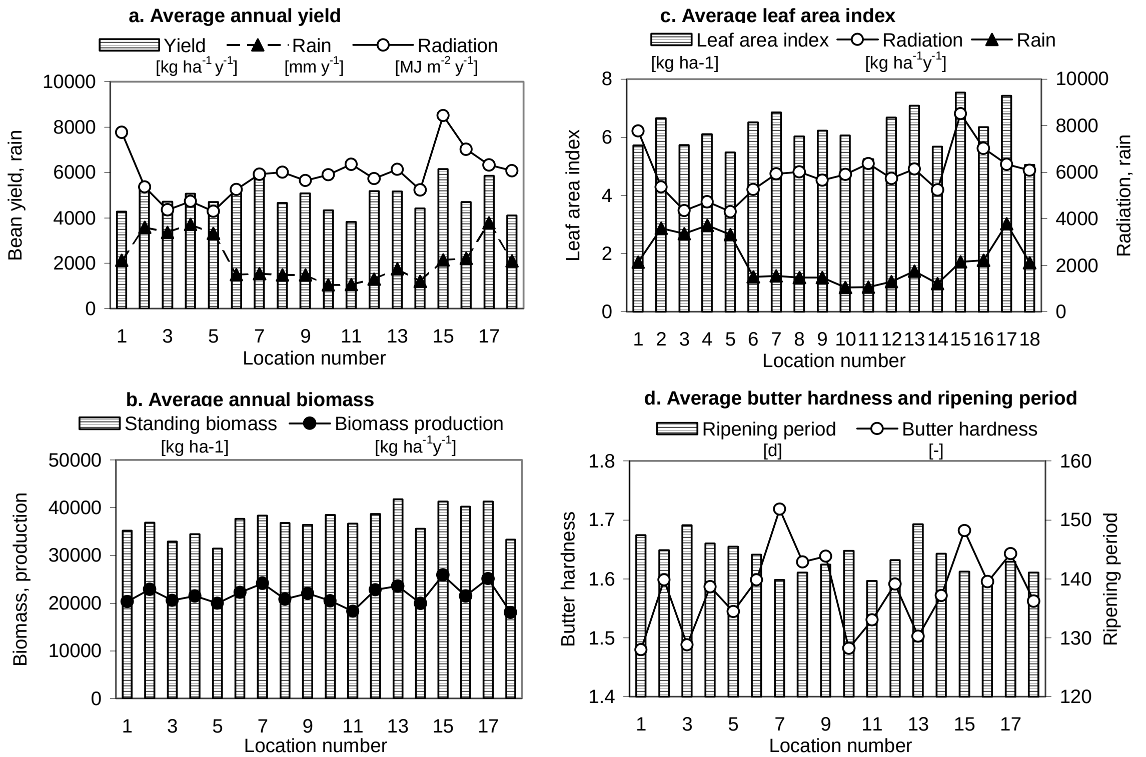


Figure 6.19. A compilation of the results of the scenario study for locations. Shown are the 10-year average values for different input and output parameters. Location numbers refer to Figure numbers (results for location 1 are presented in Figure 6.1; for location 2 in 6.2, etc.). A further discussion is provided in Section 6.3.3. Information on the locations is given in Table 6.1. Location number are 1-Brazil (Maceio, Alagoas), 2-Costa Rica (El Carmen), 3- Costa Rica (La Lola), 4- Costa Rica (La Mola), 5- Costa Rica (Puerto Limon), 6-Ghana (Tafo), 7- Indonesia (Bah Lias, Sumatra), 8- Ivory Coast (Abidjan), 9-Ivory Coast (Adiake), 10- Ivory Coast (Daloa), 11- Ivory Coast (Dimbokro), 12- Ivory Coast (Gagnoa), 13- Ivory Coast (Man), 14- Ivory Coast (San Pedro), 15-Malaysia (Tawau, Sabah), 16-Malaysia (Telok Chengai), 17- Papua New Guinea (Dami Oil Palm Research Station), and 18- Philippines (IRRI wet station site). Program codes of parameters that were used to calculate averages: yield (YYLDBN), rain (YRAIN), radiation (YRDD), biomass production (YGTOT), standing biomass (WTOT), leaf area index (YMNLAI), butter hardness (YMNBH), ripening period (YMNIPOD).

6.3.4 Availability of long-term average weather data

In order to increase the number of locations for which simulations can be carried out, long-term average weather data were collected for a number of sites. First a selection of the 10 most important cacao-producing countries was made (according to the FAO-database). These are (in alphabetical order): Brazil, Cameroon, Colombia, Ecuador, Ghana, Indonesia, Ivory Coast, Malaysia, Nigeria and Papua New Guinea. Then the availability of weather data from stations within or close to the cacao-production areas in these countries was checked and a number of stations was selected. As the CASE2 model requires information on the number of rain days per month and this data is not included in the FAOCLIM database, this parameter was taken from the Müller database (Müller & Hennings, 2000). Since the Müller database is considerably smaller than the FAOCLIM database, only a small number of stations with complete data sets remained. Table 6.2 contains information on these locations.

Table 6.2. List of locations for which simulations were carried out using long-term average weather data. Simulations were carried out for 11 years. Nr refers to the location number (program variable name LOCATION).

Nr	Country	Station	Longitude [degr.]	Latitude [degr.]	Elevation [m]
51	Brazil	Belem	-48.47	-1.45	24
52	Brazil	Salvador	-38.33	-12.9	6
53	Brazil	Vitoria	-40.33	-20.32	36
54	Cameroon	Batouri	14.37	4.47	656
55	Cameroon	Douala	9.73	4	9
56	Colombia	Andagoya	-76.67	5.1	65
57	Colombia	Villavicencio	-73.62	4.17	423
58	Ghana	Hon	0.47	6.6	158
59	Ghana	Kumasi	-1.6	6.72	287
60	Ghana	Tafo	-0.4	6.25	200
61	Ivory Coast	Abidjan	-3.93	5.25	6
62	Ivory Coast	Gagnoa	-5.95	6.13	214
63	Ivory Coast	Man	-7.52	7.38	340
64	Malaysia	Kuala Trengganu	103.13	5.33	34
65	Malaysia	Penang	100.27	5.3	4
66	Malaysia	Sandakan	118.07	5.9	12
67	Malaysia	Tawau	117.9	5.0	150
68	Papua New Guinea	Madang	145.78	-5.22	4
69	Papua New Guinea	Rabaul	152.2	-4.22	4

6.3.5 Comparing locations (long-term average weather data)

Figure 6.20 contains simulation results for the 19 locations for which long-term average weather data were available. The same parameters are included as in Figure 6.19. Similar patterns are found as in Figure 6.19, although there seems to be a closer relation between radiation and rain on the one hand and bean yield on the other. This is further tested in Section 6.3.6 using regression analyses.

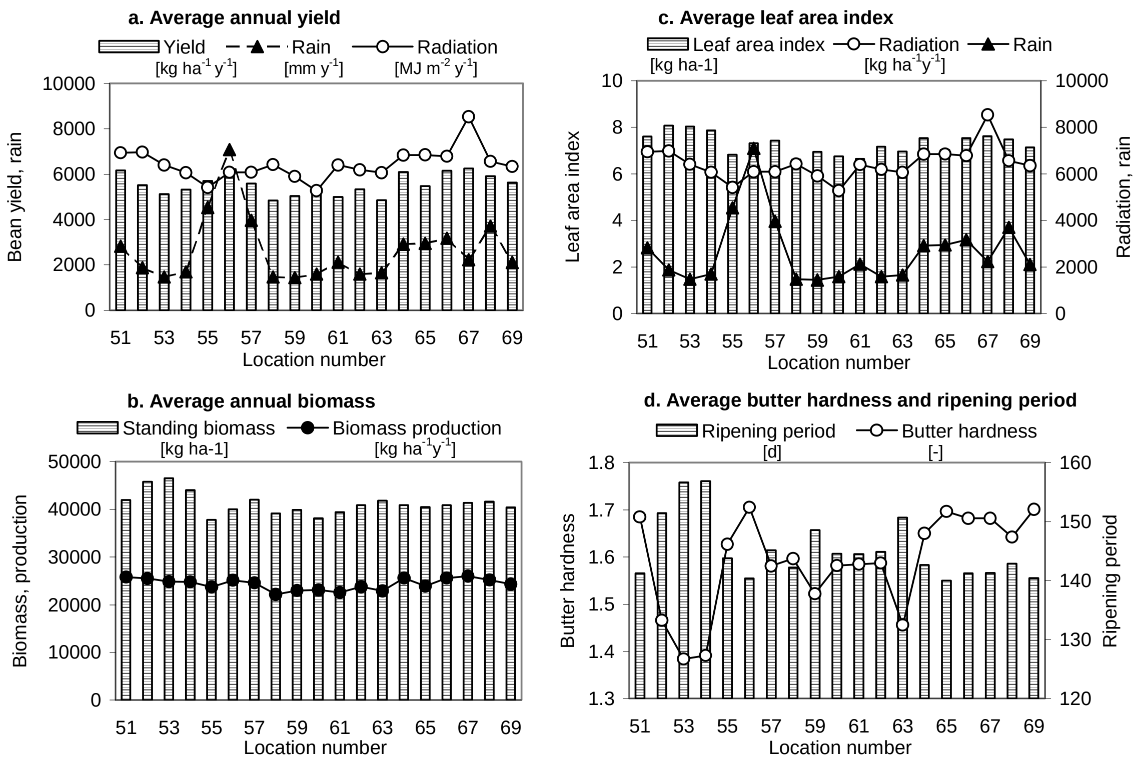


Figure 6.20. A compilation of the results of the scenario study for locations for which long-term average weather data are available. Shown are the 10-year average values for different input and output parameters. Location numbers refer to numbers in Table 6.2. Program codes of parameters that were used to calculate averages: yield (YYLDBN), rain (YRAIN), radiation (YRDD), biomass production (YGTOT), standing biomass (WTOT), leaf area index (YMNLAI), butter hardness (YMNBH), ripening period (YMNIPOD).

6.3.6 Statistical analysis

The simulation results for all locations are combined to perform regression analyses. This statistical analysis was done to determine the relation between the input parameters radiation and rainfall on the one hand and the output parameters bean yield and biomass production on the other. When such relations can be found, first (rough) estimates of yield or biomass production can be obtained by a simple calculation using radiation and rainfall. Secondly, such an analysis may reveal which of the two parameters is most important in determining bean yield or biomass production.

To prepare for the analysis, some changes were made. First, of the four locations for which both monthly and long-term average weather data are available, the simulation results for long-term weather were not used to avoid double occurrences of a location. Thus, the simulation results using long-term weather for Tafo in Ghana, Tawau in Malaysia, Abidjan and Gagnoa in Ivory Coast were not used. Secondly, two sites for which simulations were carried out for less than 10 years (Maceio in Brazil and Adiake in Ivory Coast) were removed, in order to increase the comparability of the simulation results. Thirdly, average values over a period of 9 years were calculated. These were used for the statistical test instead of the 10-year average values presented before as for several sites weather data were not sufficient to perform longer simulations. Table 6.3 contains the data used for the statistical analysis.

Table 6.3. Model input and output used for regression analyses. Values are averages over a period of 9 years, after one initial year of simulations. Locations for which less than 10 year of weather data were available, were not included in the analysis. Program variable names: Nr = LOCATION; Total tree weight = WTOTPP; Annual radiation = YRDD; Annual rainfall = YRAIN; Annual biomass production = YGTOT; Annual bean yield = YYLDBN.

Nr	Country	Location	Total tree weight [kg]	Annual radiation [MJ m^{-2} y^{-1}]	Annual rainfall [mm y^{-1}]	Annual biomass production [kg ha^{-1} y^{-1}]	Annual bean yield [kg ha^{-1} y^{-1}]
2	Costa Rica	El Carmen	36.6	5366	3536	22775	5377
3	Costa Rica	La Lola	32.5	4329	3279	20324	4652
4	Costa Rica	La Mola	34.4	4731	3714	21487	5065
5	Costa Rica	Puerto Limon	30.7	4221	3215	19622	4618
6	Ghana	Tafo	37.4	5236	1512	22146	5023
7	Indonesia	Bah Lias	38.1	5921	1538	24217	5845
8	Cote d'Ivoire	Abidjan	36.8	6009	1473	20810	4656
10	Cote d'Ivoire	Daloa	38.5	5902	1043	20462	4329
11	Cote d'Ivoire	Dimbokro	36.6	6365	1058	18281	3823
12	Cote d'Ivoire	Gagnoa	38.2	5674	1278	22354	5068
13	Cote d'Ivoire	Man	41.8	6140	1748	23590	5169
14	Cote d'Ivoire	San Pedro	35.6	5233	1207	19915	4425
15	Malaysia	Tawau,Sabah	40.9	8489	2169	25772	6118
16	Malaysia	Telok Chengai	39.8	7041	2219	21136	4589
17	Papua New Guinea	Dami	40.8	6349	3811	25020	5845
18	Philipines	IRRI	33.0	6042	2054	18054	4108
51	Brazil	Belem	41.6	6939	2784	25623	6119
52	Brazil	Salvador	45.3	6977	1859	25356	5474
53	Brazil	Vitoria	46.1	6407	1483	24698	5089
54	Cameroon	Batouri	43.7	6063	1722	24580	5269
55	Cameroon	Douala	37.4	5409	4475	23544	5662
56	Colombia	Andagoya	39.7	6090	7109	24935	6005
57	Colombia	Villavicencio	41.6	6088	4072	24609	5614
58	Ghana	Hon	38.8	6424	1480	22138	4860
59	Ghana	Kumasi	39.4	5905	1449	22688	5013
63	Ivory Coast	Man	41.3	6062	1637	22852	4865
64	Malaysia	Kuala Trengganu	40.5	6839	3003	25487	6072
65	Malaysia	Penang	40.1	6850	2974	23708	5429
66	Malaysia	Sandakan	40.6	6784	3261	25548	6126
68	Papua New Guinea	Madang	41.3	6563	3754	24989	5850
69	Papua New Guinea	Rabaul	40.0	6341	2107	24135	5592

The relations between bean yield, biomass production, radiation and rainfall are shown in Figure 6.21. One third of the variation in bean yield – as simulated by the model – is explained by differences in total rainfall (graph a in Figure 6.21). Almost one fifth of the variation in bean yield is explained by radiation (graph c). Variation in biomass production can also be well explained by differences in rainfall and radiation. Biomass production is more closely correlated with radiation than with rainfall (compare graphs b and d).

As radiation and rainfall are not correlated (this result is not shown in the graphs), they may in combination explain more of the variation in yield and biomass production. This can be tested using multiple regression analysis. In this analysis, several explaining variables may be combined to obtain one regression equation for a certain dependent variable (in this case yield or biomass production).

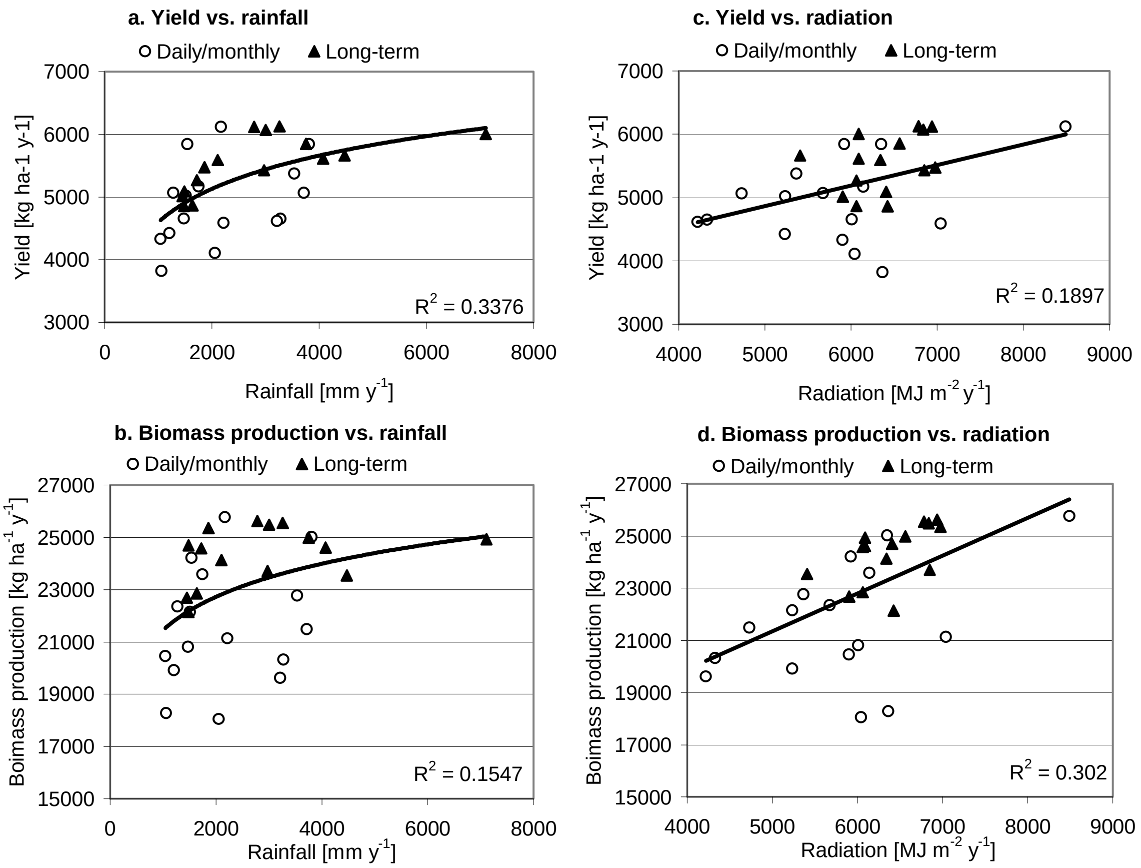


Figure 6.21. Regression lines for annual bean yield and annual biomass production vs. rainfall and radiation for 31 locations for which daily, monthly or annual weather data were available. Each point represents one location: circles are locations for which daily or monthly weather data are used; triangles are locations for which long-term average weather data were used. Values are the 9-year average values for different input and output parameters, as included in Table 6.3. R^2 values are coefficients of determination, indicating the part of the variation in bean yield or biomass production that is explained by the values of either rainfall or radiation. Linear regression was used for radiation and logarithmic regression for rainfall. The regression equations are as follows: Graph a: y = 764.13Ln(x) - 677.43; Graph b: y = 1830.2Ln(x) + 8811.2; Graph c: y = 0.3246x + 3241.1; Graph d: y = 1.4491x + 14106 . Program variable names: Annual radiation = YRDD; Annual rainfall = YRAIN; Annual biomass production = YGTOT; Annual bean yield = YYLDBN.

The results of the multiple regression analysis are shown in Figure 6.22. This figure shows how the simulated values for bean yield and biomass production can be estimated using data on rainfall and radiation. The equation that best fitted the simulated yield was:

Bean yield [kg ha^{-1} y^{-1}] = 2263 + 0.28 * Rainfall [mm y^{-1}] + 0.37 * Radiation [MJ m^{-2} y^{-1}]

This equation explains over 50% of the variation in bean yield between locations. The remaining variation is due to other factors, such as the distribution of rain in time. When a quick estimate of the potential for cocoa yield is to be made, this equation may be very useful. It should be kept in mind that this equation is based on 9-year average values (for all three parameters). It should also be noted that in this equation the *simulated* bean yield is the dependent variable, and that its value is an approximation of the actual bean yield that may be achieved. This regression equation should thus only be used as a first estimate.

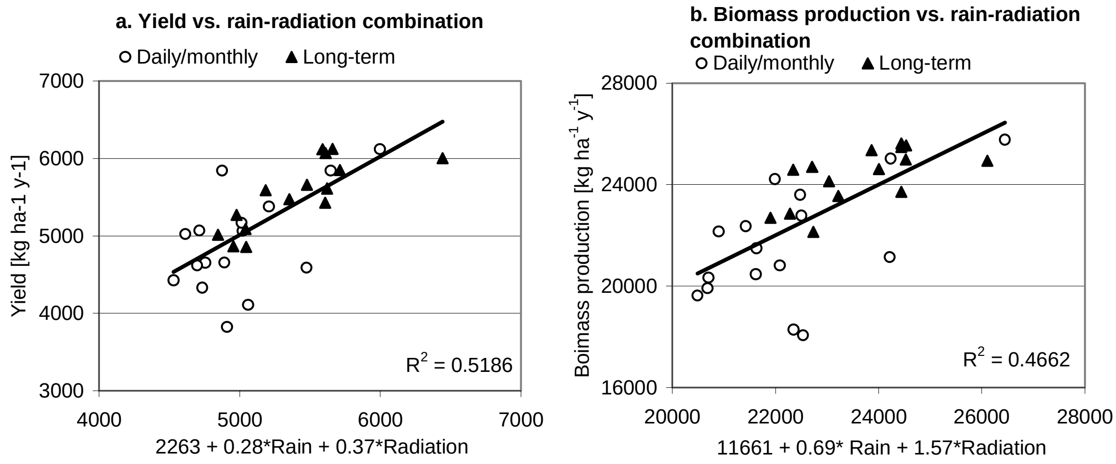


Figure 6.22. Results of multiple regression analysis for annual bean yield and annual biomass production. The simulated values for these dependent variables were regressed against the combination of rainfall and radiation for 31 locations for which daily, monthly or annual weather data were available. Along the x-axis are the values calculated according to the regression equation in which annual radiation and annual rainfall are combined. Each point represents one location: circles are locations for which daily or monthly weather data are used; triangles are locations for which long-term average weather data were used. Values are the 9-year average values for different input and output parameters, as included in Table 6.3. R^2 values are coefficients of determination, indicating the part of the variation in bean yield or biomass production that is explained by rainfall and radiation. Multiple forward regression was used. Program variable names: Annual radiation = YRDD; Annual rainfall = YRAIN; Annual biomass production = YGTOT; Annual bean yield = YYLDBN.

For biomass production the best equation is:

Biomass production [kg ha^{-1} y^{-1}] = 11661 + 0.69 * Rainfall [mm y^{-1}] + 1.57 * Radiation [MJ m^{-2} y^{-1}]

This equation explains 47% of the variation in biomass production. Also in this case, the remaining variation is explained by other factors such as the distribution of rainfall in time. Nevertheless, this equation can be used for a quick estimate of attainable biomass production in a given climate. The same considerations as mentioned above for bean yield should be taken into account.

Table 6.4 summarises the results of the regression analyses. The table shows that when the data of daily/monthly and long-term weather data are combined, more significant regressions are found and the explained variation in bean yield and biomass production is larger. This is probably due to the small number of locations of one weather type (15 or 16). For daily/monthly weather data, none of the relations is significant. The reason for this lack is not clear: the variation in bean yield and biomass production is larger for the locations with daily/monthly weather data (compared to that for the long-term weather locations). There are also more locations with low amounts of annual radiation and rainfall. The regression equations probably do not estimate well for low values of rainfall and radiation.

Table 6.4. Results of regression analyses for annual bean yield and biomass production vs. annual radiation, annual rain or both. *n* indicates the number of data points (locations) used in the regression. The data in the table are the coefficients of determination (R^2) that indicate the part of the variation in the dependent variable (either yield or biomass production) explained by the value of the independent variable (radiation, rain or both combined). ns = not significant, indicating that the relation between dependent and independent variables is not significant. Asterisks (*) indicate significance level: * = $p<0.05$ (i.e. 5% probability that the regression is not true), **=$p<0.01$ and ***=$p<0.001$. Program variable names: Annual radiation = YRDD; Annual rainfall = YRAIN; Annual biomass production = YGTOT; Annual bean yield = YYLDBN. Logarithmic regressions were used for rainfall as dependent variable.

Type of weather data	**Regression of:**						*n*
	Bean yield			Biomass production			
	vs. radiation	*vs.* rainfall	*vs.* both	*vs*. radiation	*vs.* rainfall	*vs.* both	
Daily/monthly	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	16
Long-term	*ns*	0.58**	0.67**	0.29*	*ns*	0.50*	15
Combined	0.19*	0.34**	0.52***	0.30**	0.16*	0.47***	31

6.4 Soil types

Cocoa is grown on a variety of soil types. Standard simulations of which the results are presented in this report use one soil type described in Table 3.1. This is a loamy soil with favourable water-holding capacity. To assess the consequences of differences in soil type, simulations have been carried out using two other soil types with that have a different texture and are known to occur in cocoa producing areas. Information on soil texture was taken from Wood & Lass (1985). The two soils differ in texture: one is a sandy soil, the other a clayey soil. Both have a lower water-holding capacity (difference between water content at field capacity and that at wilting point) than the “standard” soil. The three soils are compared in Table 6.5. The simulations were carried out for the three selected locations (Malaysia, Ghana and Costa Rica; see Section 6.2 for explanation).

Table 6.5. A comparison of the characteristics of three soil types related to soil texture and water-holding capacity. Soil 1 is the “standard” soil type used for all other simulations presented in this report (also described in Table 3.1). Soil 2 is based on the results of mechanical analysis for an average soil in cocoa planting areas in Rondonia, Brazil. Soil 3 is based on results of such analysis for a soil in a plantation in Tawau, Sabah, Malaysia (Table Estate). The percentages sand, silt and clay given for these soils translated into texture classes on the basis of the sand-silt-clay triangle (see for example Driessen 1986). Texture class numbers refer to the Driessen soil types: 1= Coarse sand; 7= Loamy medium coarse sand; 8= Loamy fine sand; 9= Sandy loam; 12= Silt loam; 14= Sandy clay loam; 17= Light clay; 19= Heavy clay. Water content at field capacity (pF=2.0) and wilting point (pF=4.2) are calculated using the water retention curve (Driessen 1986). Sources: Soil 1 (Wessel, 1971), Soil 2 (Table 3.8 in Wood & Lass 1985), Soil 3 (Table 3.17 in Wood & Lass 1985). Program variable names: depth of layer x (TKL(x)); texture class of layer x (TYL(x)).

Soil layer	Depth of layer [cm]			Texture class			Water content at					
							field capacity [cm^3 cm^{-3}]			wilting point [cm^3 cm^{-3}]		
	Soil 1	*Soil 2*	*Soil 3*	*Soil 1*	*Soil 2*	*Soil 3*	*Soil 1*	*Soil 2*	*Soil 3*	*Soil 1*	*Soil 2*	*Soil 3*
1	10	9	2	12	1	12	0.359	0.065	0.359	0.108	0.0001	0.108
2	30	14	54	9	7	17	0.273	0.180	0.378	0.044	0.031	0.204
3	30	12	48	8	9	19	0.233	0.273	0.493	0.027	0.044	0.361
4	150	119	52	8	14	19	0.233	0.349	0.493	0.027	0.168	0.361

Figure 6.23 shows the simulation results of the soil scenario study. The effect of soil type on yield is clearly different among the three locations: For Costa Rica, there is little difference in bean yield between the soil types, whereas for Ghana and Malaysia, large differences exists between soil 1 on the one hand and soils 2 and 3 on the other. In both cases, the difference in average bean yield exceeds 1000 kg dry beans ha^{-1} y^{-1}. The explanation for this difference is that the water-holding capacity (the difference between water content at field capacity and that at wilting point) of the soil

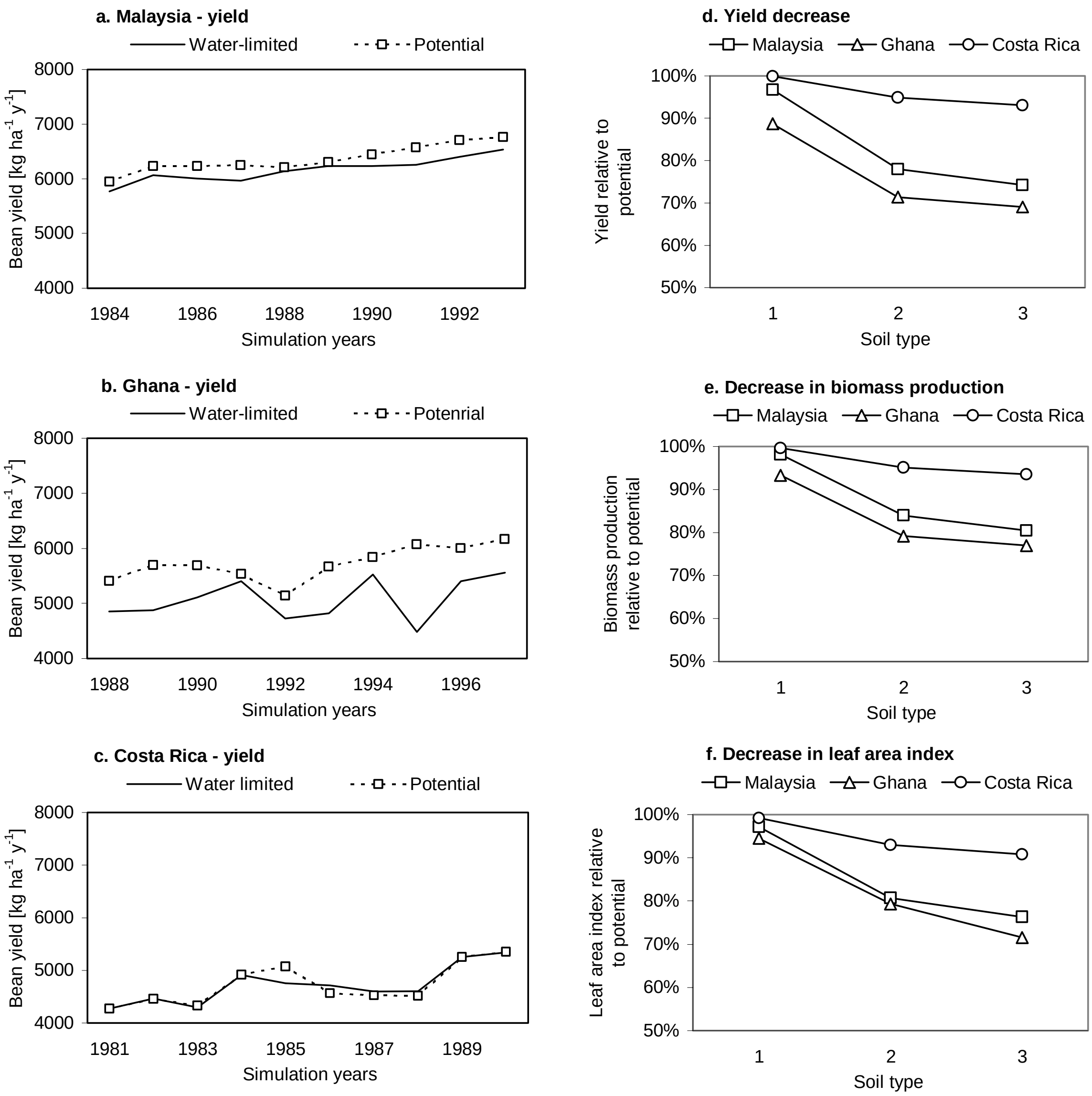


Figure 6.23. Effect of soil type on yield, biomass production and leaf area index. Shown are values for annual bean production over 10 years for Tawau, Malaysia (a), Tafo, Ghana (b) and La Lola, Costa Rica (c), as well as the relative change in bean yield (d), biomass production (e) and leaf area index (f) for different soil types. Soil 1 is the “standard” soil type used elsewhere in the report; soil 2 is s sandy soil in Brazil, soil 3 is clayey soil in Malaysia. For more information on the soil types, see Table 6.5. A further discussion is provided in Section 6.4. Program codes of shown parameters: yield (YYLDBN), biomass production (YGTOT) and leaf area index (YMNLAI).

layers in soil 1 is larger than that of the layers in soils 2 and 3. As rainfall in the Costa Rican location is very high and radiation (a variable that determines transpiration rate) is relatively low, the lower water-holding capacity of soils 2 and 3 does not strongly affect cocoa production. However, in Ghana, a lower water-holding capacity clearly affects the water availability during periods of low rainfall, and thus influences the rate of photosynthesis and the production of beans. In Malaysia, the high level of radiation possibly causes water shortage in soils with lower water-holding capacity when transpiration requires more water than available.

Graphs d-f in Figure 6.23 show very similar patterns for the relative changes in yield, biomass production and leaf area index for the three soil types. The differences in biomass production are related to the lower rates of photosynthesis during periods of low water availability and the smaller average size of the model trees in soils 2 and 3. The difference in leaf area index is also related to this size difference, and - in addition - to the higher rate of leaf fall and the lower leaf production during periods of water stress.

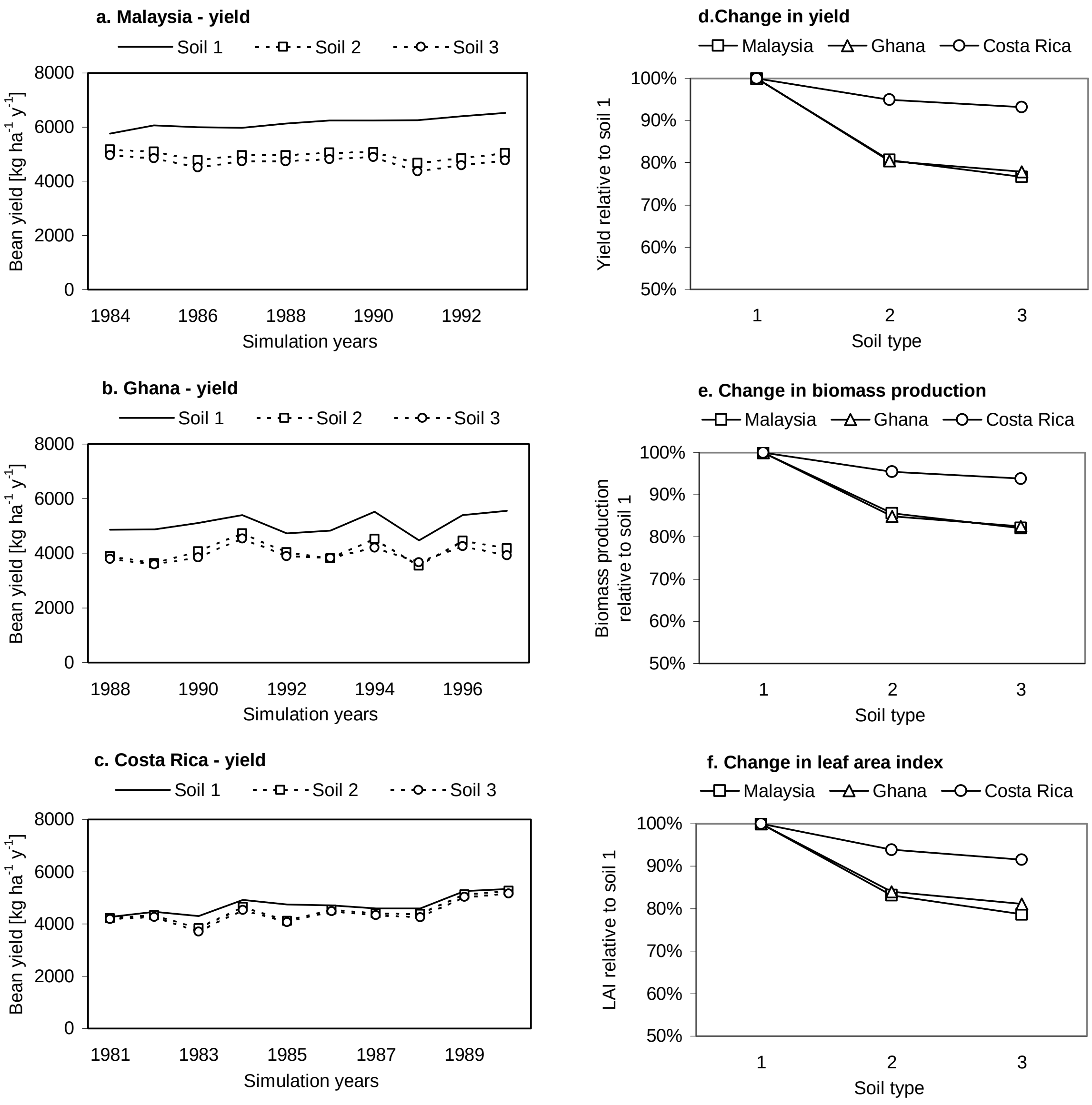
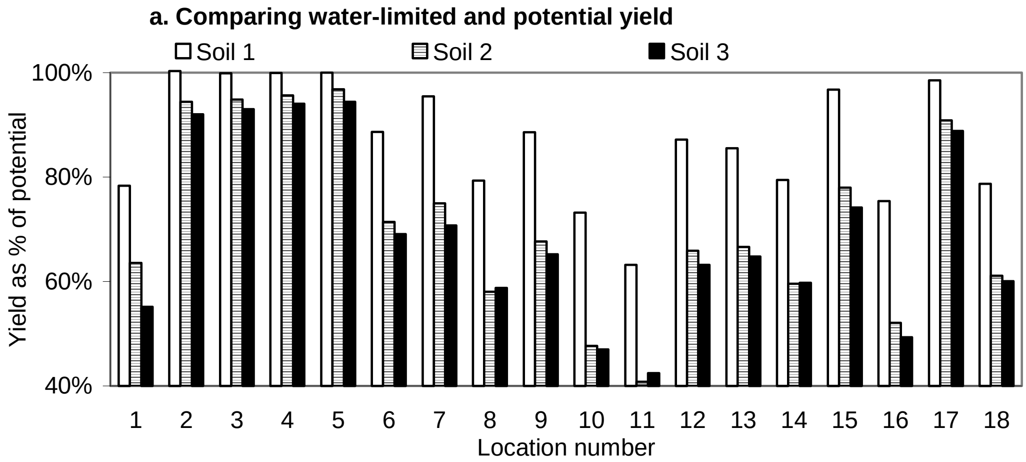


Figure 6.24. Effect of production level (potential production vs. water-limited production) on yield, biomass production and leaf area index. Shown are values for annual bean production over 10 years for Tawau, Malaysia (a), Tafo, Ghana (b) and La Lola, Costa Rica (c), as well as the relative decrease in bean yield (d), biomass production (e) and leaf area index (f) of water-limited production (compared to potential production) for three different soil types. Soil types as in Figure 6.23 and as described in Table 6.5. A further discussion is provided in Section 6.5. Program variable names of shown parameters: yield (YYLDBN), biomass production (YGTOT) and leaf area index (YMNLAI).

6.5 Water limitation

Simulations in CASE2 can be carried out for two so-called ‘production levels’. The first is potential production (production level 1) in which no limitation of water, nutrients and no pests or diseases are included. In this case, cocoa growth and yield only depends on the level of radiation and – for fruit ripening – on the ambient temperature. The second level is water-limited production (production level 2) in which production is limited by the availability of water, but not by nutrients,



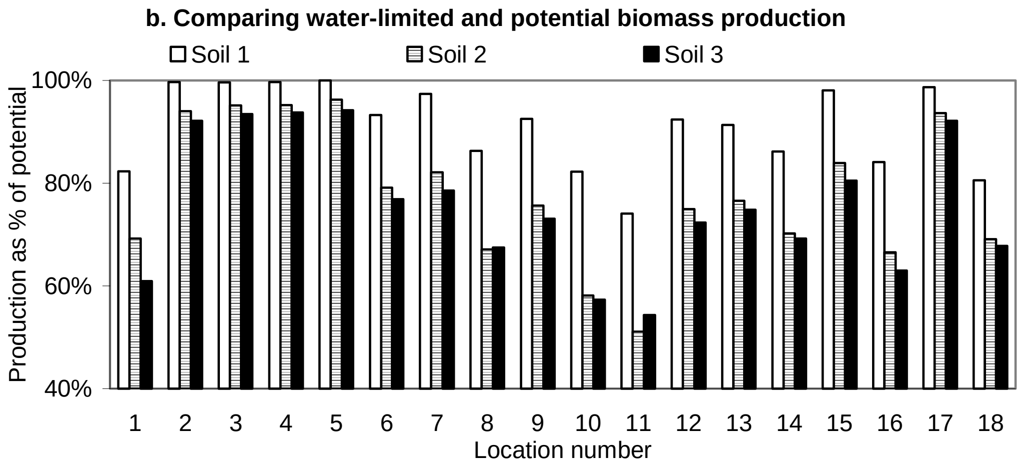


Figure 6.25. Values of annual yield (a) and annual biomass production (b) under water-limited production relative to those under potential (non-water-limited) production for 18 locations and three soil types. Information on the locations is provided in Table 6.1. Location 1. Brazil, Maceio; 2. Costa Rica (CR), El Carmen; 3. CR, La Lola; 4. CR, La Mola; 5. CR, Puerto Limon; 6. Ghana, Tafo; 7. Indonesia, Bah Lias; 8. Ivory Coast (IC), Abidjan; 9.IC, Adiake; 10. IC, Daloa; 11. IC, Dimbokro; 12. IC, Gagnoa; 13.IC, Man; 14. IC, San Pedro; 15. Malaysia; Table (Tawau,Sabah); 16. Malaysia, Telok Chengai; 17. Papua New Guinea, Dami; 18. Philipines, IRRI. Soil types are presented in Table 6.4. Soil 1 = loamy soil; soil 2 = sandy soil; soil 3 = clayey soil. The percentages were calculated using 10-year average values of potential and water-limited situations; shade = ca. 10%; tree density = 1000 ha^{-1} ; initial age = 4.1 year. For sites 11, 16 and 18 the simulations in soil type 2 and 3 ended prematurely due to long dry periods.

pests or diseases. All simulations in this report have been carried out using the water-limited situation. However, it is useful to compare simulation results for water-limited and potential production, as this provides information on the extent to which cocoa production in a certain location or on a certain soil type is limited by water availability. As both the input (rainfall) and storage of water (soil characteristic) is of importance in determining the effect of water limitation, results of the simulation runs for potential and water-limited production were compared among the three soil types presented in Section 6.4. The simulations were carried out for the three selected locations (Malaysia, Ghana and Costa Rica; see Section 6.2 for explanation).

Figure 6.24 contains the results of the water-limitation scenario. When considering the left graphs in the Figure, it becomes clear that yield reduction due to water limitation is almost nil for Costa Rica and very small for Malaysia. For climatic conditions in Ghana, the reduction in yield is highest, amounting to 10% . The long dry seasons are responsible for this yield gap. The comparison of yield reduction for the three soil types for which simulations have been presented in the previous Section, changes the picture. Graph d in Figure 6.24 shows that the pattern of yield reduction for soil 1 is different from that of soils 2 and 3. That is, the simulated yield reduction for soils 2 and 3 are much larger than for soil 1: 20% compared to 5% (when averaged over the three sites). In addition, for soils 2 and 3, the yield reduction for Malaysia is very large (25%) and comparable to that of Ghana. Water availability in Malaysia may considerably limit production in the case of a soil with limited water storage. This is probably due to the high level of radiation in Malaysia which result in large water losses by transpiration. For Ghana, soil type also has a large impact on yield reduction. Here, water availability during periods of low rainfall may be somewhat higher when water is stored in the soil. In contrast, in Costa Rica there is hardly any water limitation on yield, and the soil type does not seem to matter. The amount of rain and its distribution over the year is favourable and radiation does not lead to large water losses by transpiration. Similar patterns of yield reduction in different soil types were found for biomass production and leaf area index (graphs e and f of Figure 6.24).

The analysis of the importance of water limitation was extended to all 18 locations for which simulations have been conducted using daily/monthly weather data, again including the comparison of the three different soil types. A summary of the results of this analysis are presented in Figure 6.25. In upper graph the yield for a water-limited situation is expressed as a percentage of that for potential production, with different bar types indicating the different soil types. It is evident that there are large differences in yield reduction among the 18 locations: for the four Costa Rican sites (numbers 2-5) the simulated yield reduction does not exceed 10% for any of the three soil types, whereas yield reduction up to 50% is reached in Brazil (1), Ivory Coast (10-11) and Malaysia (16). As expected, soil 1 leads to much smaller yield reduction than soils 2 and 3, due to differences in water-holding capacity. As for yield, biomass production in water-limited situations in the 18 locations and 3 soil types differs largely among locations and soil types (graph (b) in Figure 6.25).

In conclusion, the interaction between weather conditions (mainly rainfall and radiation) and soil properties determine the level of yield reduction due to water limitation. Moderate periods of low rainfall can be partly overcome by a soil with good storage properties, thus not leading to large yield reduction in water-limited simulations (e.g. Tawau, Malaysia). For long periods with little precipitation, good storage of water in the soil may only partly overcome the low input of water (e.g. sites in Ivory Coast, Ghana and Philippines). Lastly, in the case of ample rain which is well-distributed over the year, soil properties hardly influence productivity (e.g. Costa Rica).
The large differences in simulated yields for different soil types imply that, in order to obtain region-specific estimates, it is important to carefully choose one or several representative soil types for the region.

6.6 Shade regime

The level of shade depends on two parameters, both of which are an input in CASE2. First, the extinction coefficient of the shade tree is of importance. This value determines the amount of light transmitted by a layer of leaves and depends on the spatial distribution of leaves. The second parameter is the leaf area index (LAI) of the shade trees. How these two parameters determine the portion of total radiation that is available for cacao trees is shown in Figure 6.26. This figure shows

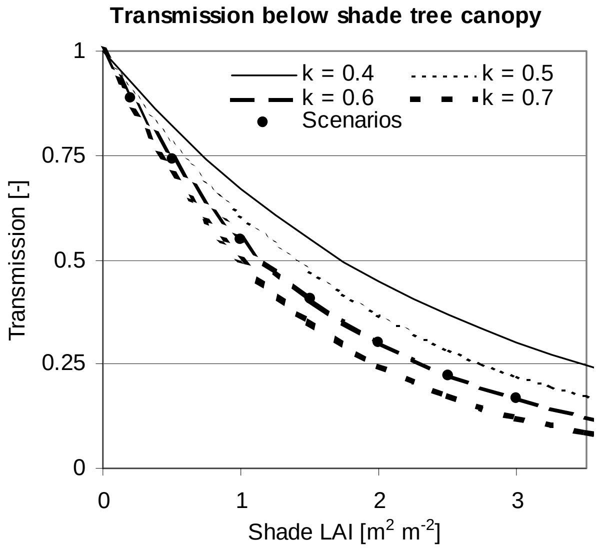


Figure 6.26. Transmission of radiation below a shade canopy, according to Beer's law and as calculated in CASE2. The transmission depends on the leaf area index of the shade trees (LAI, this is the number of leaf layers of the shade canopy) and on the extinction coefficient (k). The black dots indicate the shade levels used in the scenario study.

that the portion of transmitted light decreases exponentially with increasing LAI. The value of the extinction coefficient – which is typically between 0.4-0.7 for trees (and palms) – modifies this relation.

To determine the impact of shading on cocoa biomass production and yield, a scenario study was carried out using different shade levels. These shade levels are indicated by the filled circles in Figure 6.26. Only the value of LAI was changed to modify shading, but the same shade levels can also be reached by changing both the extinction coefficient and the LAI. Shade tree LAI values applied were (all in ha ha^{-1}): 0 (0% shade), 0.2 (11%), 0.5 (26%), 1.0 (45%), 1.5 (59%), 2.0 (70%), 2.5 (78%) and 3.0 (83%). The simulations were carried out for the three selected locations (Malaysia, Ghana and Costa Rica; see Section 6.2 for explanation). Shade levels up to 70% could be simulated for the three selected sites and up to 83% for the Malaysia site only. For the two sites, extreme shade levels caused the model tree to die as a result of low photosynthetic production combined with high "costs" of maintenance respiration. The shade level with a LAI=0.2 ha ha^{-1} is used for most simulations presented in this report (example simulations in Chapter 3, scenarios in Section 6.3.2).
Figure 6.27 contains the results of the shade scenarios for three locations (Malaysia, Ghana and Costa Rica). Parts a-c show annual simulated yields under different shade levels and over a period of 10 years. Differences in yield between the no-shade and light shading (11 and 26%) are generally small. Shade levels of >60% cause much larger declines in bean yield. The reductions in bean yield are very similar between the three locations, as shown in graph d of Figure 6.27. Considering the effects of shading on total biomass production, very comparable results are obtained (part e). The pattern for leaf area index of the model cacao trees is different (part f). The increase in LAI at shading percentages up to 60% is caused by the adaptation of the leaf morphology: at shade levels of >10%, the specific leaf area (SLA, the leaf area per unit leaf weight) is changed, being higher at lower light availability. The reduction in LAI at shade

percentages of >60% is caused by the fact that model trees remain small under heavy shading, thus having less leaves. It should be noted that the high values for LAI at intermediate shade levels are overestimates as a considerable part of the leaves in the simulated cacao canopy will receive too little light to exist. Clearly, the model needs to be further refined on this subject.

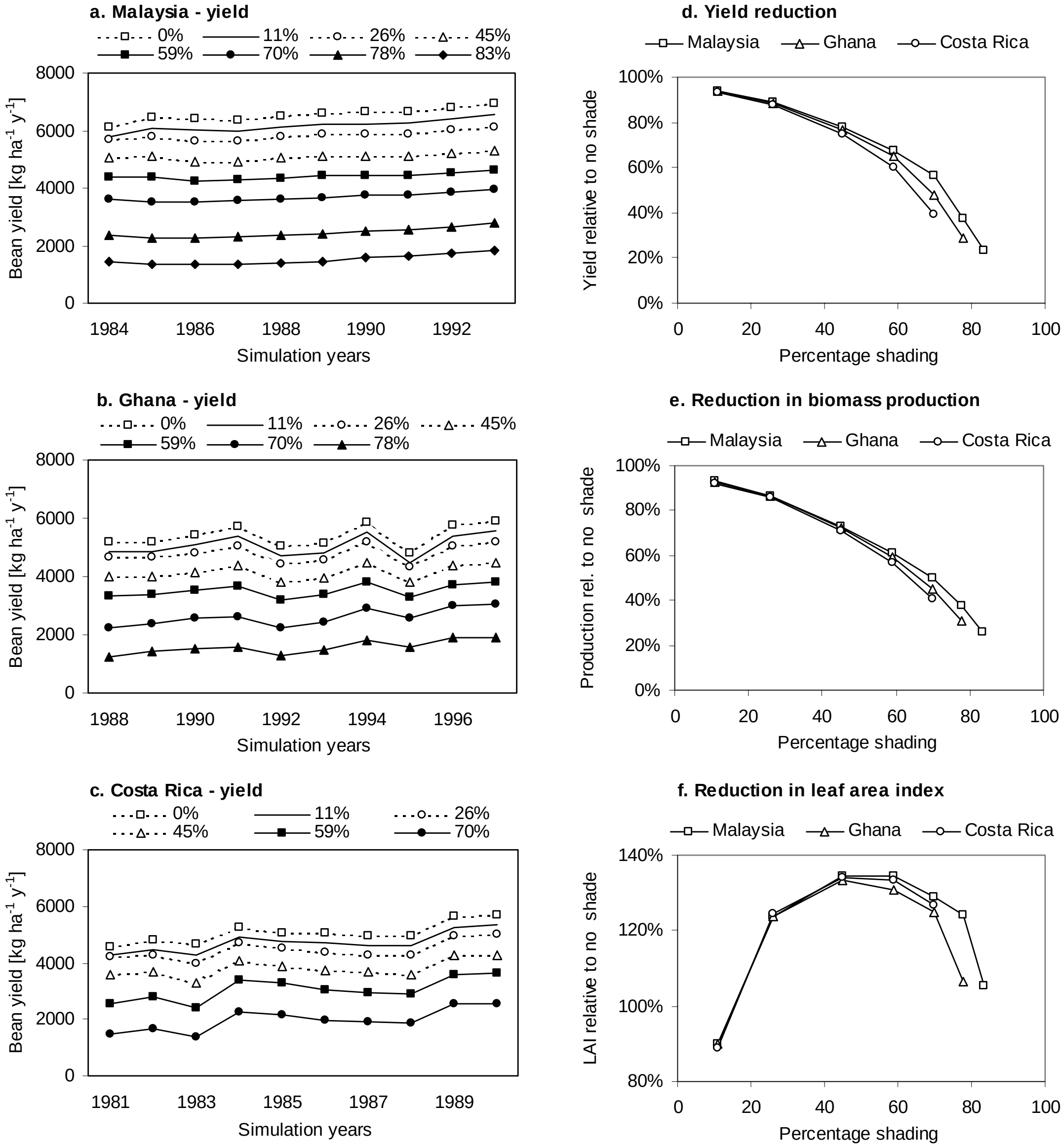


Figure 6.27. Effect of different shade levels on yield, biomass production and leaf area index. Shown are values for annual bean production over 10 years for Tawau, Malaysia (a), Tafo, Ghana (b) and La Lola, Costa Rica (c), as well as the relative reduction in bean yield (d), biomass production (e) and leaf area index (f) due to an increase in shade percentage. Percentage shading is calculated as 100% minus the percentage transmission. A further discussion is provided in Section 6.6. Program codes of shown parameters: yield (YYLDBN), biomass production (YGTOT) and leaf area index (YMNLAI).

6.7 Initial tree age

The initial age – and thus the initial size – of the simulated cacao tree may influence the biomass production and yield as larger trees generally produce more pods. A scenario study for initial tree age was carried out using 6 ages: 3, 4, 10, 15, 20 and 25 y. The standard simulation runs of which results are presented elsewhere in this report used an initial age of 4.1 years (1500 days). The simulations were carried out for the three selected locations (Malaysia, Ghana and Costa Rica; see Section 6.2 for explanation).

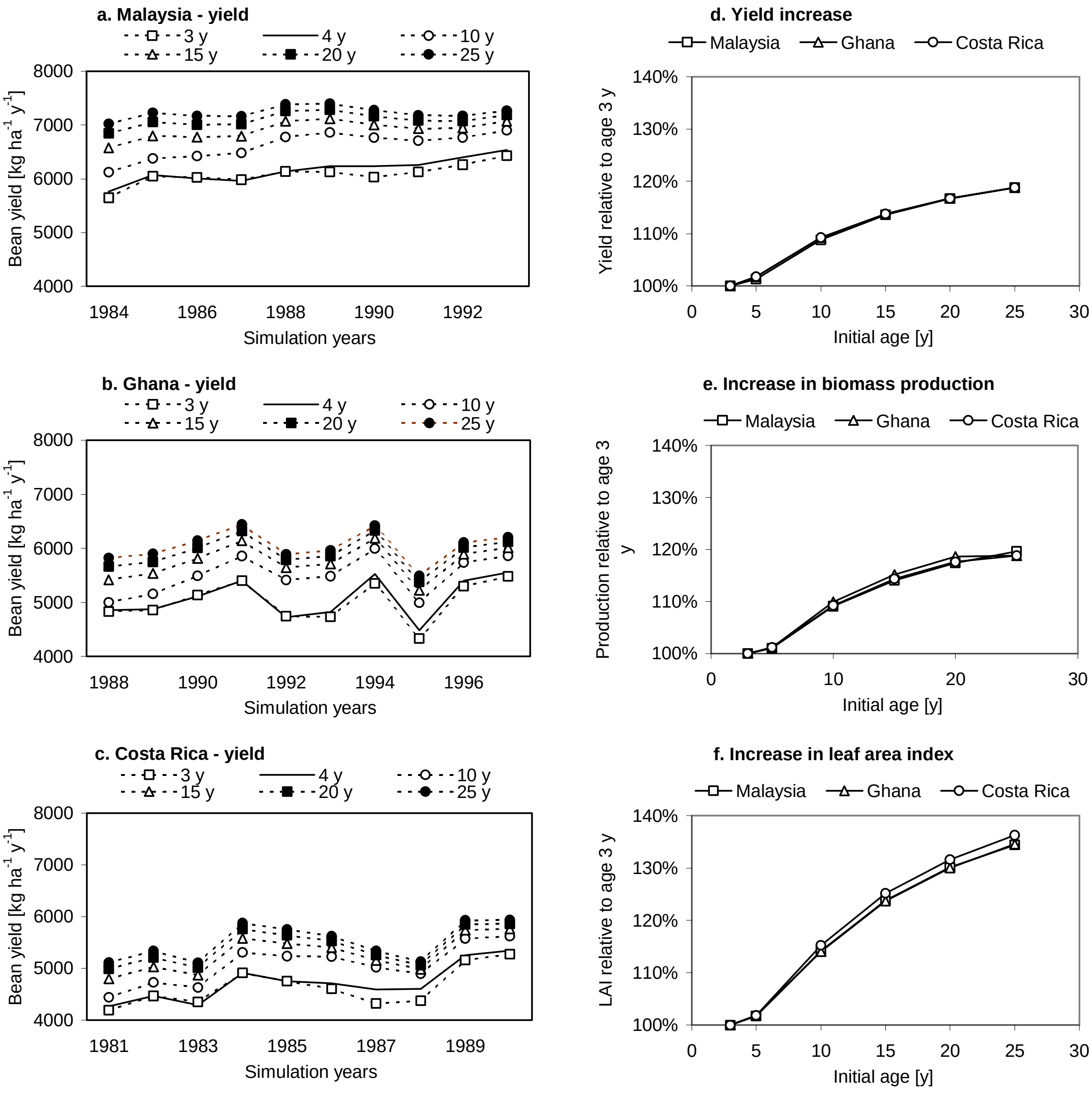


Figure 6.28. Effect of initial age on yield, biomass production and leaf area index. Shown are values for annual bean production over 10 years for Tawau, Malaysia (a), Tafo, Ghana (b) and La Lola, Costa Rica (c), as well as the relative change in bean yield (d), biomass production (e) and leaf area index (f) due to an increase in initial age. A further discussion is provided in Section 6.7. Program codes of shown parameters: yield (YYLDBN), biomass production (YGTOT) and leaf area index (YMNLAI).

Figure 6.28 shows the simulation results for the scenario study. Graphs a-c in this Figure show the influence of initial age on bean yield over a period of 10 years. In general the differences in

simulated bean yields with various starting ages are not very large. Differences between initial ages of 4 and 10 years are the most pronounced. It is also apparent that the pattern of inter-annual variation in bean yield for Ghana and Costa Rica is not affected by the initial age. Thus, in spite of the differences in tree size (not only initially but also during the 11-year simulation period), temporal variation in weather conditions has very similar effects on bean yield. The size difference between scenarios becomes smaller in the course of the simulation period. The initial tree weight for the two most extreme scenarios differed by a factor 2 (19 kg per plant for 3-y old trees and 37 kg for 25-y old trees), but for Malaysia this difference was reduced to less than 20% after 11 years (43 kg and 52 kg, respectively). This result is related to a more rapid growth of young (thus, small) model trees during the first years compared to old trees. This is illustrated in Figure 6.29 which contains the size-age relations for the different initial age-scenarios and for the three locations. In spite of the differences in initial age, all scenarios reach a similar "trajectory" in the age-size relation after some time. The level of this "trajectory" depends on the location, being higher for Malaysia. That is, under climatic conditions in Malaysia, model simulations estimate higher biomass for trees of a given age than under climatic conditions for Ghana or Costa Rica. The reason for such a "trajectory" is that net growth of the plant depends to a large extent on its weight. Plant weight determines growth as it is related to light interception (leaf area depends on leaf weight), to maintenance costs and to costs of replacement of lost plant parts (fallen leaves, etc.). The reason that during the first simulation years the weight of model trees increases rather rapidly is probably due to the initialisation of the model.
Returning to Figure 6.28, parts d-f show the increase in yield, biomass production and leaf area index with increasing initial age of the model trees. The increase in the values of these parameters with higher initial age gradually changes: at low initial age, a small age increase has a rather strong effect, but at higher ages this effect is much less. When comparing the different graphs (d-f), it becomes clear that increases in yield and biomass production are very comparable, but almost twice as low as those in leaf area index (LAI). This is related to the fact that the difference in

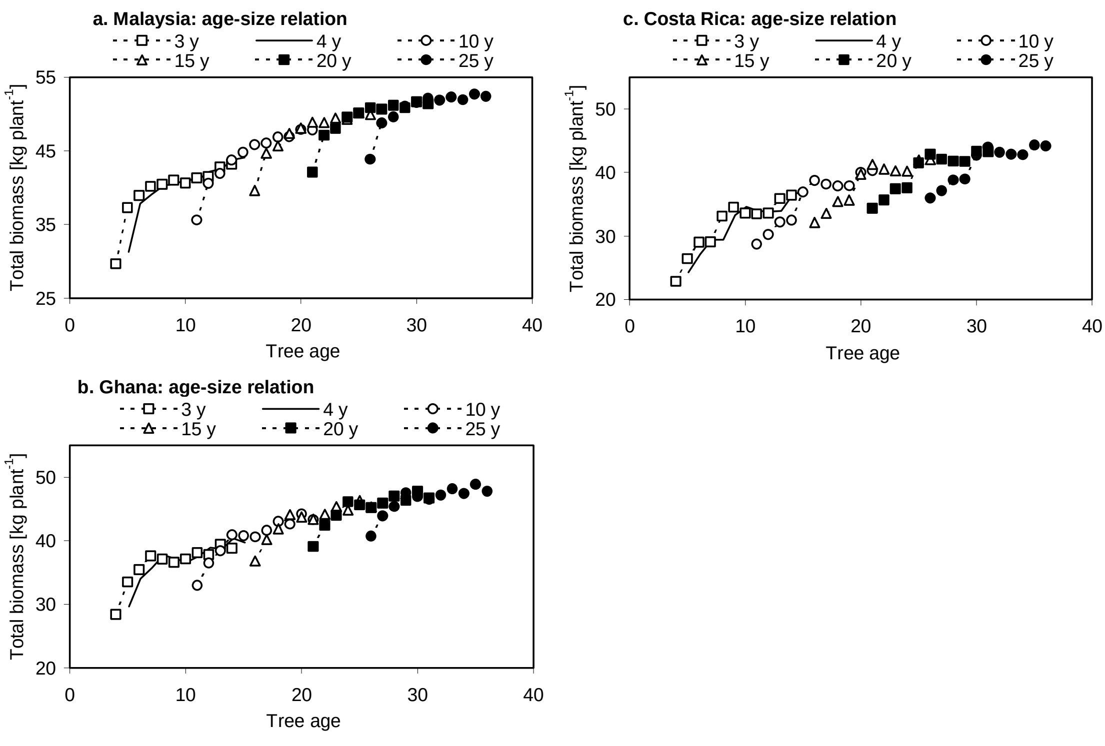


Figure 6.29. Effect of initial age on the relation between age and size for Tawau, Malaysia (a), Tafo, Ghana (b) and La Lola, Costa Rica (c). A further discussion is provided in Section 6.7. Program code: age (AGEYR), biomass (WTOTPP).

biomass among the different scenarios is rather large and the LAI is directly related to this. The difference between the increase in LAI and that in yield or biomass production is due to the fact that an increase in leaf area does not necessarily imply a proportional increase in light interception and photosynthesis. Especially at high values of the LAI, an increase in leaf area has very little effect on the interception of light, as almost all available light is intercepted and absorbed already.

6.8 Concluding remarks

A number of conclusions can be drawn on the basis of the results of the scenario studies.

(1) When comparing different locations (with different weather conditions), a large variation in yield is observed, spanning the range from 3800 (for Ivory Coast, Dimbokro) to 6100 kg ha^{-1} y^{-1} (for Malaysia, Tawau). About 50% part of this variation can be explained by the combination of rainfall and radiation in a multiple regression model. This implies that, using average rainfall and radiation, one may obtain a first estimate of the attainable bean yield, using a simple formula (see Section 6.3.6). Most probably, the remaining variation is mainly due to differences in the distribution of rain during the year. Rainfall or radiation alone explained considerably less variation in simulated bean yield.

(2) Soil texture strongly influences the simulated bean yield, by determining the capacity for water storage of the soil. Especially in areas with a notable dry season, large differences in simulated bean yield were found for different soil types. The “standard” soil type used in this report has a very favourable water storing property, thus leading to high yields (compare for instance simulated and observed yields in Figure 4.1).

(3) Water limitation may cause reductions in simulated bean yield of less than 1 to over 40% depending on weather conditions and soil type. Yield reduction due to water limitation strongly varies among the three soil types used in the scenarios. For example, for Ghana and Malaysia, the difference in yield reduction between soil types 1 (loamy soil) and soil 3 (clayey soil) exceeded 20% (that is, yield reduction in soil 3 was 20% higher than in soil 1).

(4) Shading very strongly influences plant growth and bean yield in model simulations. Shade regimes with shading of >60% (that is, less than 40% of the total radiation available for the cacao trees) have a strong effect on simulated bean yield. Shading of 80% caused a 80%-decline in bean yield compared to a situation without shade. For comparison, the relative difference between lowest and highest average yield for the 18 locations is 40%.
In the interpretation of the shading results, it is important to bear in mind that unshaded cocoa requires more nutrient inputs, has a shorter life span and cannot be combined with economically important shade trees. The negative effect of shading on production as estimated by CASE2 should be considered in this context.

(5) Initial age has a considerable impact on bean yield. As age is translated to size in the model and as tree size determines the leaf area of the model tree, higher initial age results in a higher photosynthetic productivity and thus a higher bean yield. Nevertheless, when the initial age is chosen between 3 and 10 years, the impact on average bean yield is relatively small (<10%).

7. Research and modelling priorities

7.1 Short-term and small-scale studies

A large number of gaps exist in our knowledge of the physiology, growth and production of cacao. Some of these gaps can be filled with short-term and small-scale studies (see below) whereas others require long-term and larger-scale studies (see Section 7.2).
Results of small-scale studies on the following topics may help to improve the model and the quality of its estimates without large inputs. (Some of the information may be available but should then be specifically searched for.)

(1) Leaf dynamics. Basic information on leaf dynamics is largely lacking, except for some studies and observations. Information on the life span of cacao leaves is very important for the parameterisation of the CASE2 model, as well as knowledge on the relation between leaf life span and environmental conditions (such as availability of water and light, see also Section 7.2).
(2) Heartwood formation. In the current version of CASE2, part of the wood is heartwood (dead wood that does not require maintenance costs). Heartwood is formed after 10 years, but this period is estimated, and needs to be confirmed in a wood anatomic study of trees of different age (and under different environmental conditions). Changes in the age at which heartwood is formed influence the maintenance costs of the model trees and thus their bean production.
(3) Turnover of roots. In the current version of the model, the loss of coarse lateral roots (> 2 mm in diameter) is calculated as a percentage of the weight of the lost fine roots. The latter value is based on a turn-over rate from a field study in Costa Rica. The percentage is an estimate based on the weight of lost branches relative to the weight of fallen leaves. An observed value for the turn-over of coarse lateral roots would improve the quality of model estimates.
(4) Distribution of biomass. The partitioning of assimilates in the model is based on existing allometric relations between the weight of plant parts and that of the entire tree. These relations are established with the use of information on entire cacao trees that have been harvested. The number of trees on which these relations are based is small (18 trees) as many studies have not included root biomass. Extra information on dry weight of plant parts for trees of known age and preferably for known location and shade level, improves the quality of model input and thus also that of model output.
(5) Quantification of shade level. Shade levels in cocoa plantations have only occasionally been quantified. For realistic simulations of different shade regimes, however, it is important to obtain quantitative information on shading (% transmission below shade tree canopy), or on the characteristics of shade trees (extinction coefficient and leaf area index).
(6) Data sets of climate, soil and yield. For a better validation of model results, it is necessary to obtain coherent data sets on weather, soil, yield and other production-related variables (biomass, leaf area index, etc.) for one site and one period of time.

7.2 Long-term and larger-scale studies

Several larger gaps in our knowledge and understanding of the physiology, growth and production of cocoa ask for long-term and larger-scale studies. Additional knowledge on these aspects should (largely) be derived from well-designed and extensive field studies in which the cocoa crop is studied in relation to its environment and this environment is quantified (in terms of shading, weather conditions and soil conditions).The selection below is linked to the needs for further model development which are discussed below (Section 7.3).

(1) Temporal variation in rainfall appeared to be very important in determining the simulated biomass production and yield. However, the processes that govern the adaptation of cacao trees during periods of reduced water availability are hardly quantified. For instance, the relations between leaf production, leaf fall and root production on the one hand and temporal variation in rainfall on the other, are unclear. It is also not known after how many days of water shortage cacao trees will start to show the effects of water stress.

(2) Shading is very important in cocoa cropping systems. However, shading is generally very poorly quantified and the effects of shading on growth, physiology and morphology of cacao trees have been little studied. The effects of shading on leaf production and loss, on leaf morphology (thinner leaves under low-light conditions) and on plant morphology (increased investment in leaf biomass relative to root biomass) are only partly quantified.

(3) Pruning is a common practice in cocoa plantations, but the consequences for plant morphology and physiology are unclear. How much biomass is taken away during pruning? How does this influence leaf area, light interception, growth and partitioning in cacao trees? And, to what extend would the inclusion of pruning in the CASE2 model influence model output? It is necessary to assess how pruning activities may interact with physiology and morphology of cacao trees. Depending on the outcome of such studies, CASE2 may be modified to include consequences of pruning.

(4) Although some knowledge on nutrient cycling in cocoa production systems is available, the physiological insights concerning uptake, use and re-allocation (from dying leaves) of nutrients are not known. The impact of nutrient shortage on photosynthesis, growth and partitioning of assimilates is also very poorly understood for cacao (and for many other crops). Inclusion of nutrients in the present model would therefore require extensive field studies to obtain the necessary insight in these processes. Studies on nutrient cycling require much more detailed information on soil characteristics than currently used for model simulations and probably also more than available for many cocoa growing areas. Mineralisation, leaching, denitrification and immobilisation processes should be quantified.

    Insight in nutrient cycling and use in cocoa plantation systems provides the opportunity to start bridging the gap between cocoa quality (taste) and environmental factors (nutrient availability). Knowledge on nutrient flows in the soil and the cacao tree can be combined with information on the chemical composition and the changes in chemical composition during fruit ripening. Such a comparison would require extensive field studies in which both the nutrient status of the soil and the crop as well as the chemical composition of the ripening fruits are measured in detail. It should be stressed that this study and the analysis of its results is complicated, given the large amount of processes and factors involved. Bridging the “quality-environment” gap is therefore not an easy task. A first study on the chemical analysis carried out within the framework of the Dutch Cocoa Association - Wageningen University collaboration is included in Appendix I.

7.3 Model development

What is the status of the CASE2 model at this moment and how can it be further developed? Starting with the first question, CASE2 makes use of a large share of the published knowledge on physiology and morphology of the cacao tree. This information is used both for the modelling of physiological and growth processes specific to cacao (fruit ripening, root development, leaf dynamics) and for the parameterisation of generally applicable (generic) physiological processes. Improvement of the model can be achieved in two ways. Some improvement of the model can be attained by additional information on the values used for the parameterisation of the model (see most of the topics for small-scale research mentioned in Section 7.1). However, any substantial development of the model requires new insights in the physiology and morphology of the cacao tree (see topics in Section 7.2).

Several topics require further development in CASE2:
(1) Temporal variation. The largest differences in bean yield and biomass production between locations with different climate and between soil types are due to temporal fluctuations in water availability and its consequences for leaf dynamics (and thus for photosynthesis and bean yield). Therefore, much of the conclusions drawn on the basis of model simulations depend on the way in which this temporal variation is modelled. The way in which the consequences of water limitation are modelled in CASE2 is based on physiological knowledge that is generally applicable to plants, but may be different in the case of cacao. For instance, the relation between water availability and photosynthesis rates (the latter being reduced at non-optimal water availability) is not known for cocoa trees, and is now assumed to be linear. Similarly, the relation between leaf life span or leaf production and water availability is assumed to be linear (both being lower at non-optimal water availability) as no information on alternative types of relations is currently available.
(2) Shading. The current version of CASE2 (using the standard parameterisation) seems to produce reasonable estimates of yield reduction in the presence of moderate to heavy shading. However, the model estimates unrealistically high values for leaf area index at intermediate shade levels. There is also a need to validate the simulation results, but information on yield gaps due to shading is scarce. Furthermore, the physiology of trees under heavy shade is probably different in reality as they may be much more efficient in photosynthesis (making optimal use of small sun flecks) and in leaf dynamics (with leaves living longer).
(3) Leaf dynamics. Several factors influence the production and fall of leaves. Two of these factors – light availability and water availability – vary largely among locations and cropping systems. As the goal of CASE2 is to compare simulated production in different regions and cropping systems, it may be important to model leaf dynamics in more detail and in relation to these environmental parameters. However, more information on leaf dynamics in relation to these parameters is needed (see Section 7.2)
(4) Nutrient limitation. The current version of CASE2 does not cope with the limitation of nutrients. Inclusion of this aspect in the model would allow for the estimation of additional nutrient requirements of different cropping systems at different locations and on different soil types. However, it would also greatly increase the complexity of the model.

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Appendix I: Results of bean quality analyses

This appendix contains results of studies on changes in the chemical composition of cocoa beans during ripening. The objective of this study was to obtain information the chemical composition of cocoa beans and changes in this composition during fruit ripening. These studies were carried out in Ghana (1998) and Malaysia (1997). Beans were collected at different dates during ripening between 100 and 180 days after pollination (DAP) at intervals of 10 days. Chemical analyses were performed at the laboratories of Gerkens Cacao, ADM Cocoa and SGS. The main results of the chemical analyses are included in this appendix. These graphs are derived from two research reports by H.R. Kattenberg (ADM Cocoa, report numbers 1228). For both locations, the general patterns in both the chemical composition of cocoa beans and the changes in this composition are similar.

The main conclusions drawn by Kattenberg are:
The most important changes in chemical composition of the beans takes place between 100 and 140 days after pollination (DAP). During this period the final chemical composition (and thus quality) of the cocoa beans is determined.
(1) Nib fat content increases from 20 to 52%;
(2) Parallel to this, there is a decrease in the weight fraction of the shell, the protein content and the ash percentage;
(3) The starch content increases;
(4) Levels of sugars, purines and catechines show a maximum value. In beans from Ghana, no sucrose was found and catechine levels steadily increase instead of showing a peak. The theobromine levels for Ghana are clearly higher than those for Malaysia.
(5) pH drops from 6-7 to 5 between 120 and 150 days after pollination (DAP);
(6) Regarding fats, an increase in the triglyceride level is observed at the cost of levels of free fatty acids, mono- and diglycerides. Within the fatty acids, there is a shift from C16 to C18 fatty acids and from saturated to unsatured fatty acids.

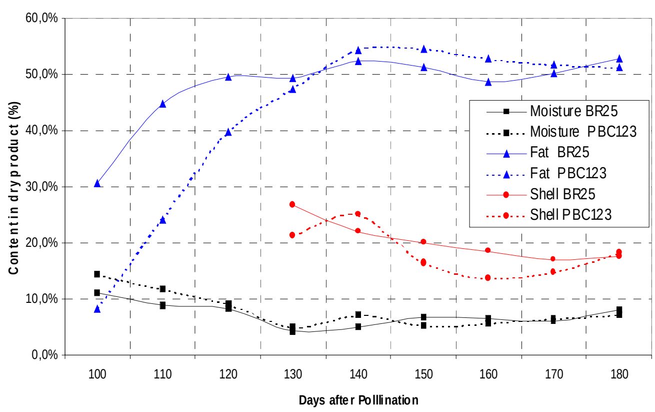
The results of these studies are comparable with those presented in a study by Bucheli and others (Bucheli *et al.* 2001) in which the chemical composition of cocoa beans from two varieties in Ecuador is determined in the course of fruit ripening. The amount and development of total fat content, the distribution of different fatty acids and the changes in levels of glucose, fructose, sucrose, theobromine and caffeine in the course of fruit ripening are all similar in the two studies.

Clearly, in order to relate information as presented here to environmental circumstances such as the availability of light, water and nutrients, bean quality studies should be accompanied by intensive data collection on environmental circumstances. Care should also be taken to exclude those factors from the experiments that may also influence the chemical composition of beans, e.g. variety or hybrid, weather conditions, plant size and shade level. In this way, the study can focus on one or two important factors determining cocoa quality, most probably including nutrient availability in the soil. Alternatively, one may specifically include different factors such as weather conditions, shade levels (or yield levels: high yielding vs. low yielding plots), but in this case care should be taken to collect sufficient samples (from different trees) for each of the treatments.

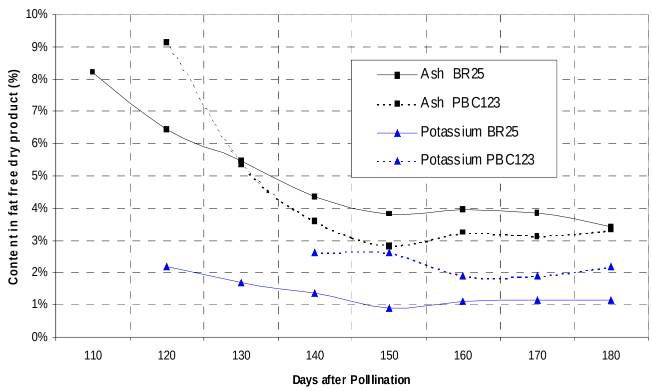
- Results for Malaysia

Figures are numbered App 3 - App 13 and contain information on two hybrids: BR25 (hybrid of BR25 x BAL244) and PBC123 (PBC123 x BAL 244).

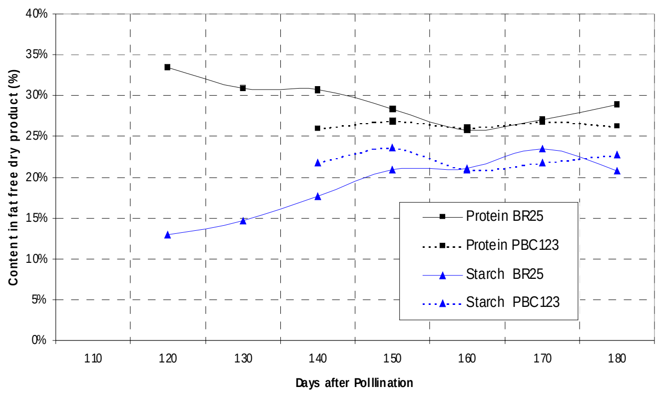
App. 3 : Moisture, fat, and shell in Cocoa Beans during Ripening



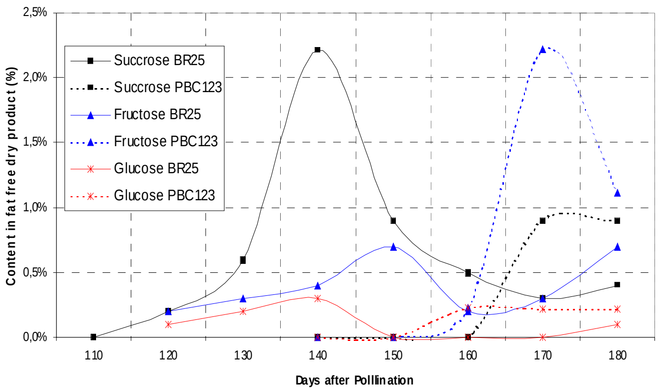
App. 4: Ash and potassium in Cocoa Beans during Ripening



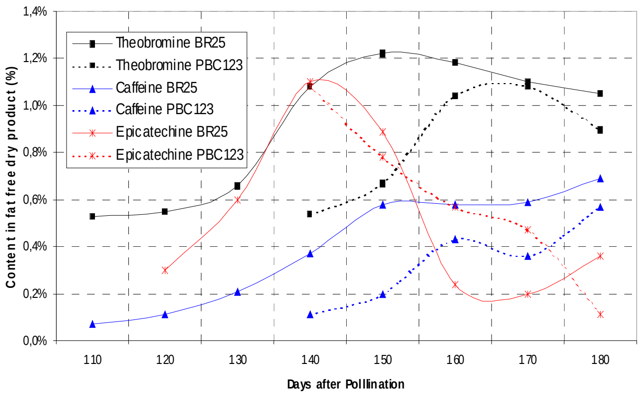
App. 5: Protein and Starch in Cocoa Beans during Ripening



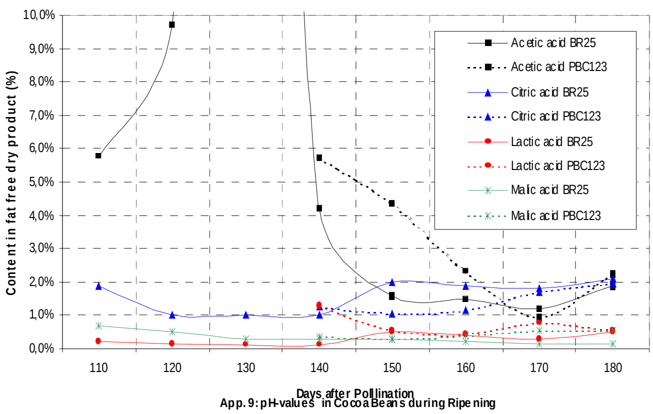
App.6 : Sugars in Cocoa Beans during Ripening



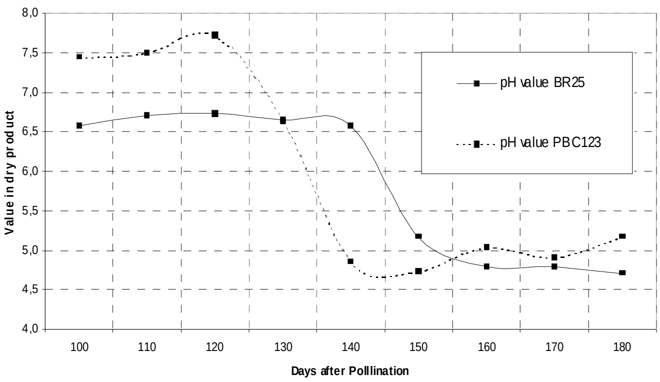
App.7 : Purines and Catechins in Cocoa Beans during Ripening



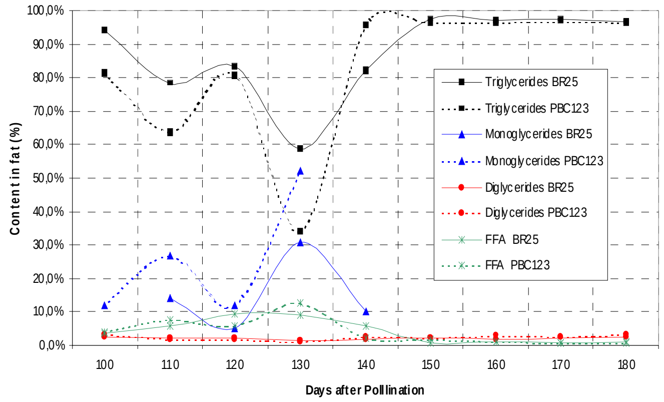
App. 8 : Acids in Cocoa Beans during Ripening



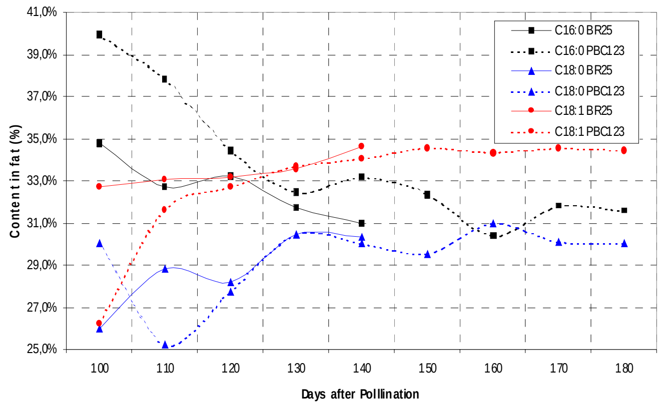
App. 9 : pH-values in Cocoa Beans during Ripening



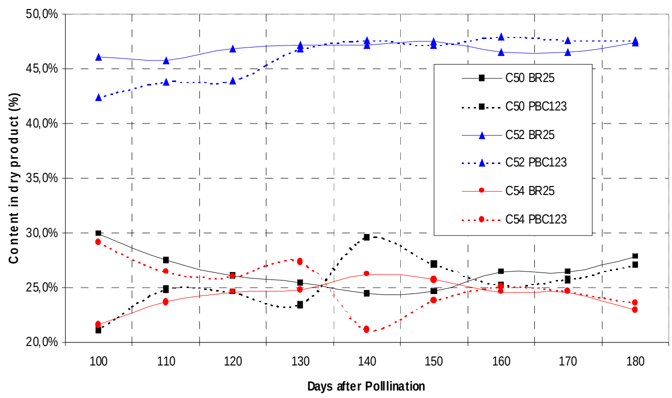
App. 10 : Mono-, di-, triglyceride and FFA in Cocoa Beans during Ripening



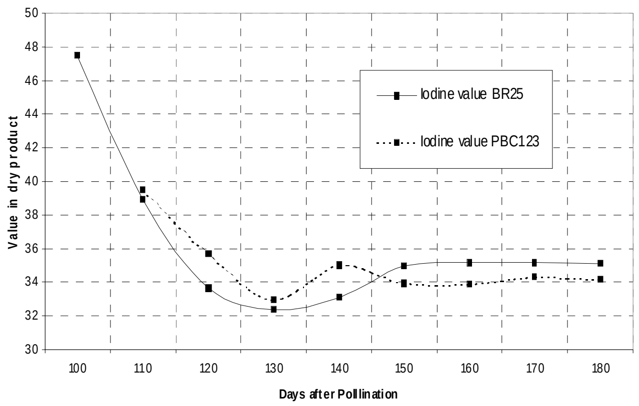
App. 11 : Fatty acid composition in Cocoa Beans during Ripening



App. 12 : Triglyceride composition in Cocoa Beans during Ripening



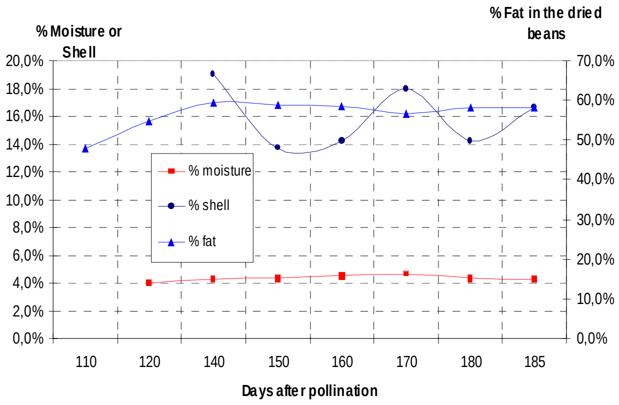
App. 13 : Iodine values in Cocoa Beans during Ripening



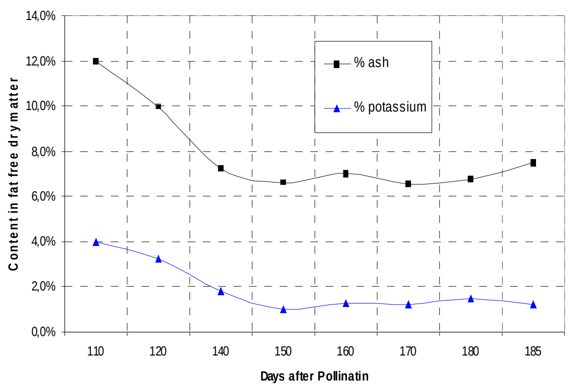
- Results for Ghana

Figures are numbered App 2 - App 12.

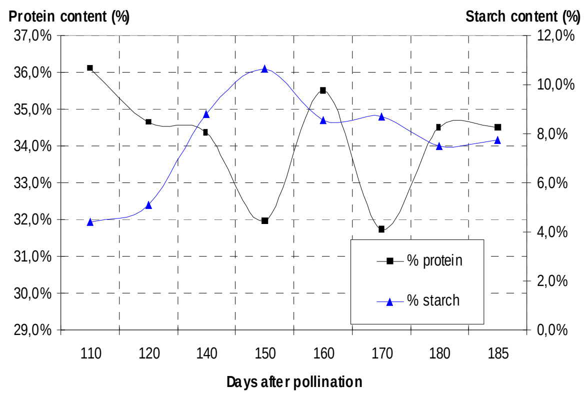
App. Sub-2: Moisure, fat and shell in cocoa beans ex Ghana during ripening



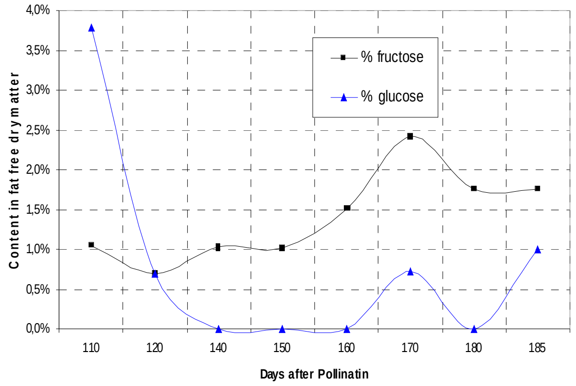
App. Sub-3: Ash and Potassium in Cocoa Beans Ex Ghana during Ripening



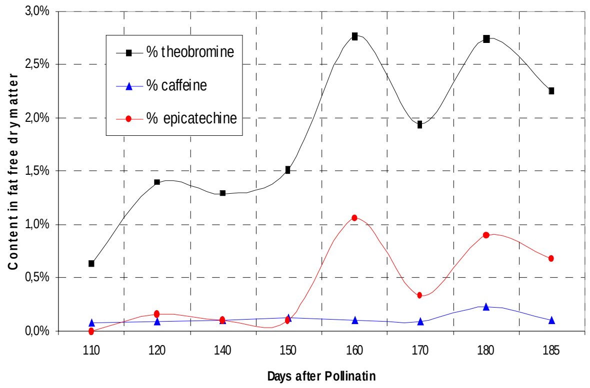
App. Sub-4: Protein and Starch in cocoa beans ex Ghana during ripening



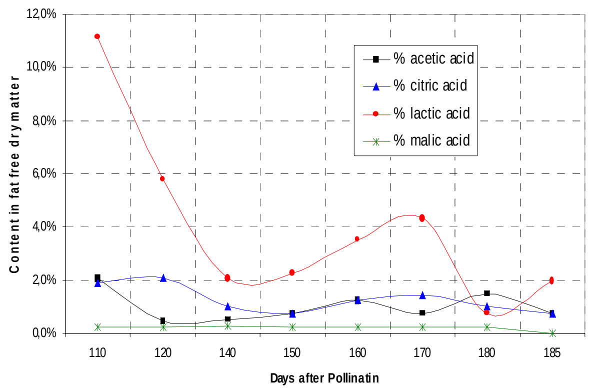
App. Sub-5: Fructose and glucose in Cocoa Beans Ex Ghana during Ripening



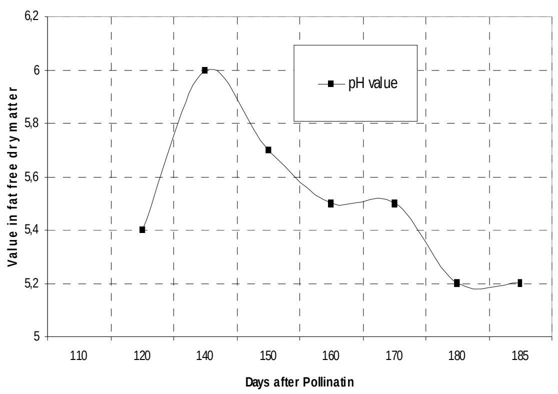
App. Sub-6: Purines and Catechins in Cocoa Beans Ex Ghana during Ripening



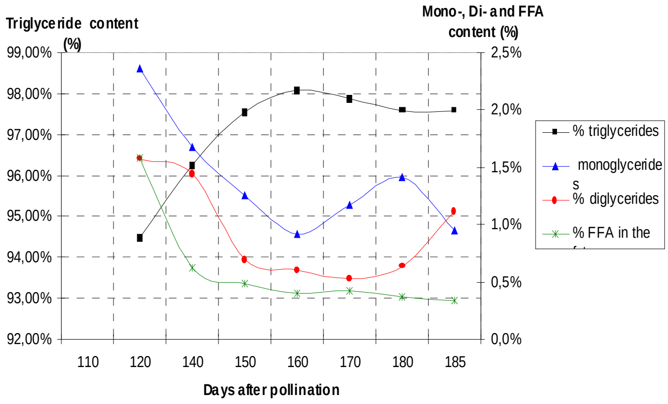
App. sub-7: Acids in Cocoa Beans Ex Ghana during Ripening



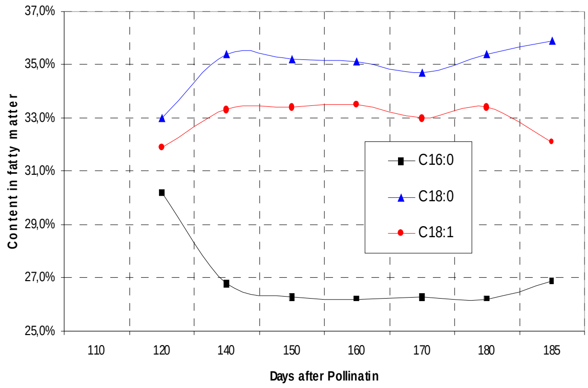
App. sub-8: pH in Cocoa Beans Ex Ghana during Ripening



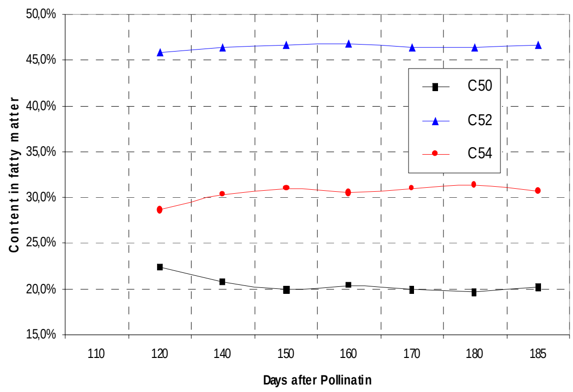
App. Sub-9: Composition of Fat in cocoa beans ex Ghana during ripening



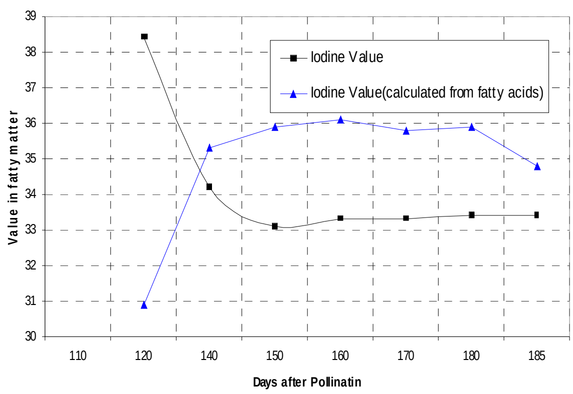
App. Sub-10: Fatty acid composition in Cocoa Beans Ex Ghana during Ripening



App. Sub 11: Triglyceride composition by C-number) in Cocoa Beans Ex Ghana during Ripening



App. Sub 12: Iodine value in Cocoa Beans Ex Ghana during Ripening



Appendix II: Comparing model results for daily and monthly weather

This appendix contains a comparison of model output using daily and monthly weather data for a location in the Philippines (IRRI wet station site). CASE2 may be used for both daily and monthly weather. When monthly weather information is used, the model itself will derive daily values by interpolation between the values of a parameter for subsequent months in the case of radiation, temperatures and vapour pressure. For rainfall, daily rain is generated using information on the amount of rain, the amount of rain days for a particular month and the probabilities that a rain day is followed by a day without rain and vice versa. As simulation results using both types of weather data are used and compared, it is necessary to check whether there are large differences in model output.
Figure II.1 shows the results of the comparison for environmental parameters (radiation and rain in graph a and b) and yield estimates (c and d). Graph a shows that in general there is a good agreement between the observed rainfall (positive values) and the generated rainfall based on monthly information (negative values). Both the size and the timing of the generated rainfall peaks on the basis of monthly data are comparable to the observed values. Radiation (graph b) is less variable using monthly weather data, but values used for the monthly weather data follow the observed daily trends. As for yield, graph c shows that yield estimates on the basis of monthly weather data are somewhat higher than those using daily weather data. This difference is confirmed in graph d for annual yield. On an annual basis, the difference in yield is 10% and is statistically significant. The explanation for this difference is probably that periods without rain are less severe when using monthly weather data: the total amount of rain in a month is spread over the entire month and cannot all fall during the first week, leaving the rest of the month without rain. It is expected that this difference is smaller when rainfall is more evenly distributed over the year. The 10% difference should therefore be considered as a maximum value.

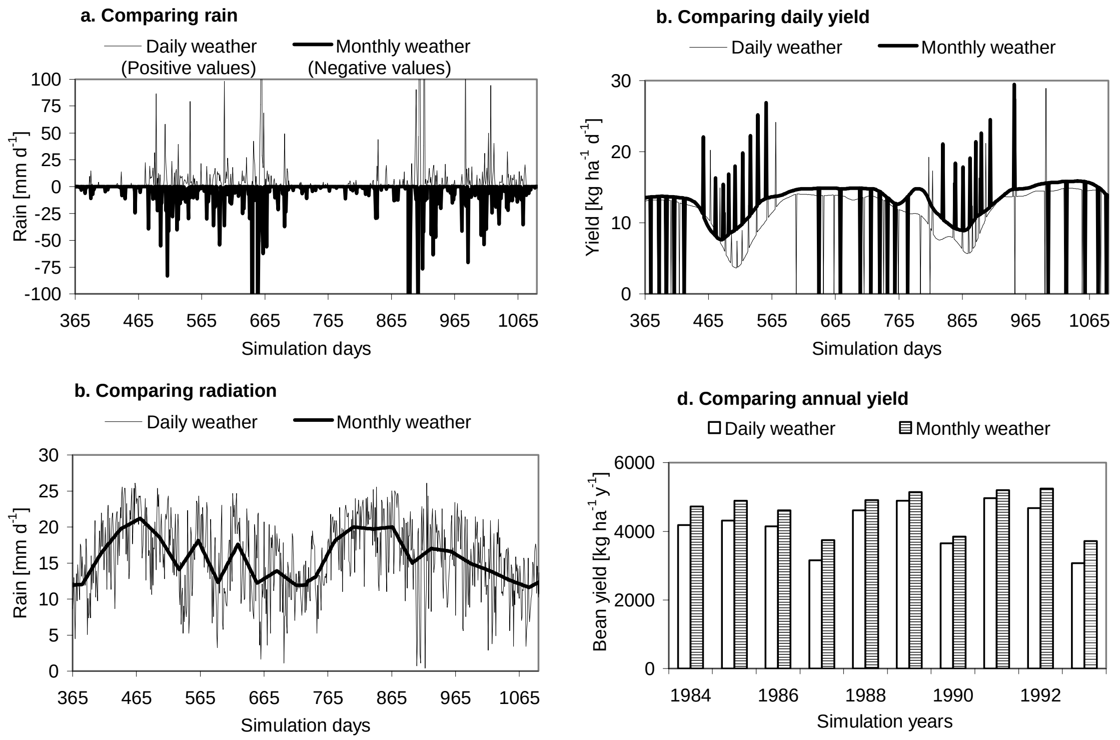


Figure II-1. A comparison of simulation results using monthly and daily weather data for IRRI in Philippines for the period 1983-1993. Rainfall (a), radiation (b) and yield (c) are compared on a daily basis for the second and third simulation year. Annual yield (d) is compared for years 2-11 of the simulation. In graph (a) simulated rain for monthly weather data is shown as negative values for the sake of clarity. Information on the location is given in Table 6.1. The soil type used for these simulations is described in Table 3.1. Tree density = 1000 ha^{-1}; initial age = 4.1 year (1500 days); shading = approximately 10%.