

Original Article

COCOA'S TRIAL BY FIRE: ANALYZING DROUGHT DURATION IMPACT IN GHANA'S TRANSITION ZONE

Kofi Agyeman Ampadu and Kwame Mensah Osei

Department of Agriculture Engineering and Mechanization, College of Agriculture Education, University of Education, Winneba, P.O. Box 40, Mampong-Ashanti, Ghana.

Abstract: Cocoa production is highly sensitive to climate change, with rainfall patterns playing a crucial role in cocoa yield. Poor rainfall distribution has led to increased droughts and seedling mortality, adversely affecting flower stability, pod development, and ultimately cocoa production. Climate change projections indicate that these conditions will worsen, particularly in West Africa, where drying trends are expected to continue.

The anticipated rise in global temperatures and the subsequent increase in potential evapotranspiration (ET_p) will exacerbate the hydrological cycle and drought stress on cocoa crops. Water deficits in mature cocoa plants have a detrimental impact on yields and make them susceptible to pests like capsids.

Cocoa trees thrive in temperatures ranging from 18-21°C minimum to 30-32°C maximum, with a preference for temperatures between 29-32°C. Higher temperatures, especially during the seedling stage, can be detrimental to cocoa plants. In regions where mean annual rainfall falls below 1250 mm, the loss of moisture due to evapotranspiration can surpass precipitation levels, leading to prolonged droughts during critical growth stages.

Keywords: Cocoa production, climate change, rainfall patterns, drought stress, temperature sensitivity, evapotranspiration, West Africa.

1.0 Introduction

1.1 Background

According to Oyekale et al. (2009), cocoa is highly sensitive to climate change and responds to it quickly. Kotir (2011) has established a significant correlation between cocoa yield and rainfall. Poor distribution of rainfall has resulted in increasing frequency and length of droughts and seedling mortality. The resultant condition affects flower stability, pod growth and development.. These conditions have been predicted to get worse in West Africa with further increase in the drying capacity of the current climate scenario (Kotir, 2011). The projected increase in global temperature and the corresponding increase in potential evapotranspiration (ET_p) will intensify the hydrological cycle and drought stress on cocoa. Water deficit in mature cocoa plant, according to Läderach et al. (2013), negatively affects yield and exposes the crop to capsids attack and damage.

The temperature in cocoa growing areas usually lies between a minimum of 18-21°C and a maximum of 30-32°C. Cocoa tree needs temperature between 29-32°C as it is sensitive to higher temperature, especially at the seedling stage. Where the mean annual rainfall drops below 1250 mm, moisture loss from evapotranspiration is likely to exceed precipitation and may intensify and prolong drought at the critical stage of the crop's life which will necessitate supplementary irrigation. (Meteorological Service Agency, 2007).

Cocoa is described by Wood et al. (1987) as being sensitive to drought but there is paucity of field studies on mature cocoa tree's response to monthly increments in drought length. Gateau-Ray et al. (2018) showed that

Original Article

drought, not stating the duration, caused 15 % cocoa tree mortality and significantly decreased yield by 89%. The effects of drought on the yield of cocoa beans, published by Vos et al. (1999) were due to El Nino-Southern Oscillation (ENSO)-related droughts based on interviews with farmers and official national statistical data indicated 19 % decrease in yield in Ecuador's 1997–98 ENSO. Schwendenmann et al (2010) reported, in detail, how 13 months drought (rainfall exclusion) experiment was imposed on a six (6) years old cocoa and how it responded in 10 % decrease in yield during the rainfall exclusion in agroforestry system but recorded 45 % decrease in yield at the end of the drought period. A physiological production model with data from 30 cocoa growing areas in 10 cocoa producing countries revealed that drought was responsible for 50% decrease in yield (Zuidema et al. (2005). These reports show that many cocoa growing areas affected by climate change have significant reductions in cocoa production due to drought but none of the studies focused on the effects of intensity and duration of drought.

Farmers in the study area have observed that the area has been experiencing increasing drought lengths over the last three to four decades leading to massive loss of seedlings, flower and young pod abortion and ultimately decreased yields, especially post-dry season harvest. Trends in annual and seasonal magnitudes and frequencies in rainfall and actual evapotranspiration in the study area are posing greater challenges to improving production sustainability through adopted improved varieties, cost-effective crop and resource management, including subsidized inputs (fertilizers and seedlings) replanting. Forecasts expect a production shortfall in the coming years even though the mean annual rainfall in the study area has increased by 11.1%, annual mean major and minor season rains have increased by 10.2% and 16.1% respectively in the 2000-2009 decade (Kotei et al., 2016). However, the distribution in the current decade may not favour maximum growth and sustained yield of cocoa as the number of rainfall days has dropped by 3.96% (Kotei et al., 2016). The annual mean maximum and mean temperatures have increased by 1.2 % and 1.16 % respectively between 1980-2009 (Kotei et al., 2016). Generally, there is an increase in the mean decadal daily drying ability by 10.2 % (1980-2009) from 3.4 mm to 3.8 mm (10.2%) in the 2000-2009 decade (Kotei et al., 2016). Nieuwolt et al. (1982) published that the suitable area for cocoa growing should experience not more than one month drought annually. However, in the study area, the drought lengths vary from 2 to 5 consecutive months. Carr and Lockwood (2011) posited that, under the current climate conditions, drought severity and length are greater threats than high temperature to cocoa. Huan et al. (1986), reported results from a drip irrigation experiment in Malaysia, a warmer zone compared to the study area, and found a yield increase from 1500 kg ha⁻¹ to 2400 kg ha⁻¹ (60 % increase in production).

The objectives of irrigating cocoa are to extend its production to areas with limited rainfall, improve yields in transition zones by eliminating or reducing drought length. The Government's efforts to increase cocoa bean production to over one million Metric tonnes by 2020 could not be achieved in the study area and this could be attributed to increasing intensity and length of the dry season which varies between three (3) to five (5) months putting greater stress on cocoa. This study investigated how the Cocoa hybrid would respond to monthly incremental dose of the new drying capacity of the air (ETa) (10.2 % increase) in its yield parameters. This will help determine the degree of influence of irrigation, in the dry season, and supplemented irrigation, in the rainy season, the critical length of drought, in months, on cocoa under the current climate condition.

The study was aimed at finding out the effects of drought length on the yield parameters of cocoa in a changed climate through drip irrigation. Specifically the study was to find out the effects of drought length on the Size of cocoa pods; number of cocoa pods per plant; weight of fresh cocoa pod; number of beans per pod; weight of hundred dried cocoa beans and compare the response of the continuously irrigated trees to the major rainy season yield.

2.0 Materials and Methods

2.1 Study area

Original Article

The study area is located in the Forest-Savannah transition zone, about 62.0 km north of Kumasi. The pattern of rainfall suitable for cocoa is found within longitude 1.30-1.35°W and latitude 6.35-6.40°N of the equator and the world's cocoa lies between these belts (Meteorological Services Agency, 2007).

2.2 Climate, soil type and site

Mampong-Ashanti experiences double maximum rainfall with the major rainfall season commencing from March and ending in July with the minor rainfall also beginning from September and ending late in November. The mean annual rainfall is between 1270 mm and 1524 mm. It has a fairly high and uniform temperature ranging between 20°C in August and 32°C in March (Meteorological Services Agency, 2007). The savannah Ochrosol is dominant in the area. The soil characteristics are deep red sandy loam, well drained and with satisfactory water, holding capacity. The pH range is 6.0-6.5). The soil belongs to the Bediese series (Ghana classification) and is classified by the FAO/UNESCO legend as Chronic Luvisol) (Asiamah et al., 2000).

2.4 Experimental design and treatments

Six (6) treatments with four (4) replications were arranged in a Randomized Complete Block Design (RCBD). The treatments included: T₀: No irrigation (control); T₁: Cocoa trees with one (1) month drought.; T₂: Cocoa trees with two (2) months drought.; T₃: Cocoa trees with three (3) months drought; T₄: Cocoa trees had four (4) months drought.; T₅: Cocoa trees with continuous daily irrigation throughout the period.

2.5 Irrigation

The 13 years old cocoa trees were irrigated with 30 litres per day per plant as published by Balisima et al. (2007). Irrigation schedule is presented in Table 1. No rainfalls were recorded during the dry season (November to March).

Table 1: Planned Irrigation for drought length treatments

Treatments	Months				
	November	December	January	February	March
T ₀	N	N	N	N	N
T ₁	N	□	□	□	□
T ₂	N	N	□	□	□
T ₃	N	N	N	□	□
T ₄	N	N	N	N	□
T ₅	□	□	□	□	□

□ (Irrigated months); N (Months with no irrigation)

2.6 Cultural practices

The experimental units were selected from a mature cocoa farm at the College of Agriculture Education's experimental cocoa farm. The following cultural practices were carried out to enhance healthy growth of the cocoa trees so as to produce reliable results from the research work. The cocoa plantation had formed a canopy which controlled weed growth. The few woody perennial and shade tolerant weeds were slashed and the young shoots (chupons) growing on the trees pruned. Pruning was also carried out to remove mistletoe growing on some of the selected trees, all existing fruits and unwanted branches to ensure effective air circulation and to prevent

Original Article

excessive canopy formation to encourage adequate light penetration to reduce the incidence of capsid and black pod disease attack on the cocoa. All the pods on the cocoa trees were harvested before the treatments were applied.

2.7 Fertilizer application and pest control

Di-grow, a liquid organic fertilizer, was sprayed on the cocoa trees which served two purposes; it served as fertilizer and at the same time controlled some pest's effects on the pod. Seventy-five mills (75 ml) of Digrow Red and Green were mixed with 15 litres of water and sprayed on the leaves, flowers and fruits using a motor brow to ensure close to 100% canopy coverage. The green D.I Grow was sprayed three times at three weeks interval starting from the first week of treatments followed by the red D.I Grow, three times at the same rate and application interval.

2.8 Harvesting and drying of beans

Matured pods were harvested half or completely ripped, shelled and fermented. The beans were put in small baskets with labels on them and covered with banana leaves and were turned every two days until fermentation of six (6) days was achieved as practiced by the cocoa farmers. The fermentation process, as a traditional practice to develop the chocolate taste, color and scent and kill the embryo of the seed so that it cannot germinate during storage or processing, remove the pulp or the mucilage surrounding the seeds to make subsequent drying easier and lastly to make the beans more brittle and easier to separate from the seed coat. After the fermentation process, the beans were spread on a raised platform in the sun. Drying was done slowly in order to prevent shrinking of the beans and to ensure continuation of the biochemical processes which started during fermentation. The beans were labeled according to the treatments and replicates from which they were harvested.

2.9 Data collection and analysis

Data were collected on the number of pods per plant, the length and girth of pods, number of beans per pod, pod weight and the weight of 100 beans. The lengths of the cocoa pod were measured using a meter rule and the girth by means of venire caliper. Weight of the cocoa pod and 100 beans were taken with an electronic scale. The data collected were analysed using ANOVA and the means separated by LSD at 5.0 % probability level using Genstat statistical tool.

3.0 Results

4.1 Number of pods per plant

The pod yield reduced with increasing drought lengths. Between T_0 (rain fed cocoa) and T_4 there was no significant difference ($p < 0.05$) (Table 2). T_5 (year round irrigated cocoa) produced the highest effect of 28 pods, indicating an increase of 21 pods (300.0%) over T_0 (rain fed), 4 pods (17 %) over T_1 (trees with only one month drought) and 16 pods (133 %) over T_2 , 17 pods (155 %) over T_3 and 20 (250 %) over T_4 (rain fed trees). Statistically there was no significant difference ($p < 0.05$) between T_0 (rain fed) and T_4 , between T_2 , and T_3 . There was significant difference between the continuously irrigated trees (supplementary) (T_5) and the rest of the treatments (Table 2).

Table 2: The effects of drought length on yield parameters of 'Series II', a bi-parental hybrid of Amelonado and Trinitarios Cocoa

Treatment	Number of pod/plant	Number of beans/pod	Weight of pod (g)	Weight of 100 dried beans (g)	Volume of Water applied (Litres)
T_0 (Control)	7	26	287	46	0
T_1 (1month drought)	24	39	624	116	3,600
T_2 (2month drought)	12	36	575	107	2,760
T_3 (3month drought)	11	32	484	96	1,830

Original Article

T ₄ (4month drought)	8	29	445	87	900
T ₅ (No drought)	28	47	735	124	4,530
Mean	15	35	525	96	
LSD (0.05)	3.92	3.23	107.4	1.52	
C.V (%)	17.4	5.2	11.2	0.9	

Table 3: Mean yield of Ghana's 'Series II' hybrid Cocoa in the Wet Season (May-July) in the ForestSavannah Transition Zone

Trees	Number of pods per plant	Number of beans per pod	Weight of 100 beans (g)
Plant 1	34	55	135.00
Plant 2	29	53	130.00
Plant 3	24	58	136.00
Plant 4	33	49	127.00
Mean	30	54	132.00
Continuously irrigated trees (T₅)	28	47	124.0
Difference: Rain fed over irrigated (%)	2	7	8.0

4.2 Number of cocoa beans per pod

There was significant difference ($p < 0.05$) between the continuously irrigated trees (T₅) and the rest of the treatments (T₀, T₁, T₃, and T₄) with respect to the number of cocoa beans per pod (Table 2). The cocoa plants that were irrigated throughout the year (T₅) again recorded the highest number (47) of beans per pod (Table 2) indicating an increase of 21 beans (81 %) over T₀, 8 beans (21 %) over T₁, 11 beans (31 %) over T₂, 15 beans (47 %) over T₃ and 18 bean (62 %) over T₄.

4.3 Weight of Cocoa Pod

Drought length applied to cocoa plants significantly ($p < 0.05$) influenced the weight of cocoa pods (Table 2). T₅ (No drought) trees produced the highest weight (735g) of cocoa pod and followed the trends in the number of pods per tree and the number of beans per pod.

4.4 Weight of 100 dried cocoa beans

Statistically there was significant ($p < 0.05$) difference among the periods of drought given to the cocoa trees on weight of 100 dried beans (Table 2). It also followed the trends in number of pods per plant, number of beans per pod, weight of pod per tree. Again, T recorded the highest (124.0 g), indicating 78.0 g (17 %) over the control (T₀) and 8.0 g (7 %) over T₁ (one month drought), 17 g (16 %) over T₂, 28 g (29 %) over T₃ and 37 g (43 %) over T₄.

4.5 Comparing the Wet Season and Dry Season Yield Parameters

Table 3 indicates mean number of pods per plant (30), number of beans per pod (54) and weight of 100 beans per pod (135.0 g) from four (4) cocoa plants selected at random at the end of the major rainy season as major rainy season yield. This data helps to appreciate the difference between rain fed cocoa yield parameters and that of the irrigated yield parameters because of the difference in intensity of climate variables and their influence on pollination, young pods stability, growth and development and the ultimate yield parameters under different degrees and duration of water stress. The difference between the mean weight per bean of the major rainy season

Original Article

and that of the continuously irrigated trees in the dry season was 0.08 g just as between it (T) and T₁ (one month drought).

4.6 Comparing Irrigated Cocoa with the Control

The results in Table 4 indicate the difference between the yield parameters of control and the irrigated treatments. The one month drought treatment (T₁) and continuously irrigated cocoa trees (T) compared to the control (T₀) (no irrigation) recorded the lowest drop (4) in number of pods per plant, 8 in number of beans per pod, 220 in number of beans per plant, 0.08 g in the mean weight per bean per plant, 289.6 g in beans yield per plant using 930 litres of water less than T₅ (Table 4)

Table 4: Comparison of T₅ and T₁ in excess over T₀ (control)

Treatment	Number of pods per plant	Number of Beans per pod	Number of beans per plant	Weight per bean (g)	Yield per plant (g)
T ₅	21	21	441	0.78	343.98
T ₁	17	13	221	0.70	154.70
T ₂	5	10	50	0.61	30.50
T ₃	4	6	24	0.50	12.00
T ₄	1	3	3	0.41	1.23
Difference between T₅ and T₁	4	8	220	0.08	189.28

T₅ and T₁ increases

values between T₀ and all the treatments. The number of beans per pod is basically influenced by success of pollinating agents in pollination. Cocoa is insect pollinated crop and the population and activities of the insects are directly influenced by climate variables like temperature and relative humidity. Studies by Arnold et al. (2017) revealed a relationship between rainfall and relative cocoa pollinators (Diptera: Ceratopogonidae), abundance. According to them, during drought periods, midge numbers and activities are very low, consistent with their larval ecology, which could be worsened by intense and prolonged droughts and may result in poor pollination of the already fragile flowers. This condition is exacerbated by the low relative humidity with long droughts and hence lower number of beans per pod. Cocoa beans are the base for making chocolate and comparing T₅ with T₁ (one month drought), the 4 pods and 8 beans difference does not give economic significance per tree as 10 pods are needed to produce 1 kg of cocoa paste considering the 930 litres of water application difference. The highest number of 47 beans is above the average of 40 beans published by Michon (2016).

5.3 Weight of Cocoa Pods per Tree

The study indicates that eliminating the drought period on cocoa plant increased the pod weight in T₅ by 448.0 g (156 %), 17.79 g (111 %) and 290.0 g (65.17%) over T₀ (control) T₁ (one month drought) and T₄ respectively. This again can be explained by the increasing water stress and increasing drying capacity of the air with increasing intensity and length of drought.

5.4 Weight of 100 dried cocoa beans

From the results it could be inferred that a tone (1,000 kg) of beans produced in the dry season, under rain fed, can be increased by 1.7 tones (1,700 kg) by supplementary irrigation in the new climate of the study area. The seed weight reflects a relationship between source and sink of photosynthate during pod filling stage as optimum supply of water under optimum climatic factors promote optimum growth and development in reproductive parts of the crop. The number of pods, number of beans per pod and the weight of 100 beans per plant were all higher

Original Article

than the T₅, the highest in the dry season irrigation, indicating the importance of optimum climate variables for optimum yields apart from moisture in cocoa (Table 3).

5.5 Comparing the Wet Season and Dry Season Yield Parameters

Studies by Mohr and Schopfer (1994) revealed the influence of season on flowering pattern of cocoa. Flower production is primarily controlled, either directly or indirectly, by climatic factors and was observed that the plants that were irrigated throughout the year recorded lower number of pods (28) per plant in the dry season (November–March) compared to that in the rainy season (30) (May-July) when the relative humidity was higher and there was enough water for all pollinating agents. Prolonged periods of drought significantly lowers flowering intensity, lowers the population of pollinators and subsequent pod setting and development which are reflected in this study where seasonal variability in rainfall and temperature persist (Alvim, 1977). The flowering intensity was influenced by warm climate and increased rainfall which is greatest between April and June, promoting the population of pollinators in the major rainy season of the study area. The increase in rainfall in May-July promoted higher flowering intensity than that observed in January-February, though both months were warm (Alvim, 1977). Again, water stress caused more shedding of flowers, immature pods and production of smaller seeds, with increasing drought stress (Boutraa and Sanders, 2001).

5.6 Comparing Irrigated Cocoa with the Control

Under water stress, plants would not receive adequate nutrient supply (Dantuma and Thompson, 1983) and would have negative effects on the vegetative growth especially plant height for sunlight and number of branches and leaves for photosynthesis which may have resulted in the decreasing value in all the yield parameters. Cocoa if irrigated can save one month irrigation water without any significant drop in yield.

6.0 Conflict of Interest

The author declares that he has no conflict of interest.

7.0 Conclusion

Drought intensity and length in the new climate of the study area had significant effects on the yield parameters of cocoa. Significant differences were observed between the rain fed (control) and the other treatments in all the parameters examined. Cocoa trees with continuous irrigation were significantly and positively influenced the most in all the yield parameters. All the parameter studied decreased in value as the drought length increases. Irrigation can improve the low dry season harvests in terms of number, size and weight of cocoa beans and increase the income of farmers and government's revenue where water is available in sufficient quantities and farmers will be supported technically and financially to apply scientific irrigation for both supplementary and dry season irrigation.

6.0 Recommendations

Having gone through over 9 months experimental period for determining the effect of monthly doses of drought up to five months applications of 30.0Litres of water to cocoa plants, it is recommended that the study is replicated on a different soil in the same ecological zone on matured trees since different soils respond differently to evapotranspiration.

7.0 References

- Alvim, P. de T. (1977). Cocoa. In *Ecophysiology of tropical crops*, (Alvim, P. de T. and Kozlowski, T.T., eds.), London. Academic Press. p. 279–313.
- Arnold, S.E.J., Bridgemohan, P., Perry, G. B., Spinelli, G. R., Pierre, B., Murray, F., Haughton, C., Dockery, O., Grey, L., Murphy, S. T., Belmain, S. R. and Stevenson, P. C. (2017). The significance of climate in the pollinator dynamics of a tropical agroforestry system. *Agriculture Ecosystems & Environment*. Vol. 254.

Original Article

- Asiamah R.D., Adjei-Gyapong T., Yeboah E. Fening, J.O., Ampontuah E.O. and Gaisie E. (2000). Soil characterization and evaluation of four primary cassava multiplication sites (Mampong, Wenchi, Asuansi and Kpeve) in Ghana. SRI Technical Report No. 200, Kumasi.
- Balisimah, D. and Apshara, S. E. (2007). CPCRI: Cocoa breeding and physiology in India: Gro-Cocoa. Issue 11(5-7).
- Boutraa, T. and Sanders, F. E. (2001) Influence of water stress on grain yield and vegetative growth of two culti-vars of bean (*Phaseolus vulgaris* L.). *Journal of Agronomy and Crop Science*, 187, Pp. 251-257.
- Dantuma, G. and Thompson, T. (1983). Whole crop physiology and yield components. In: Hebblethwaite, P.D., Ed., *The Faba Bean (Vicia faba* L.). A Basis for Improvements , Butterworth, London, 143-159.
- Gakpo, J. O. (2012). Why Ghana is Cocoa and Cocoa is Ghana. Accessed 03 March, 2017. Available from <https://www.modernghana.com/news/398737/why-ghana-is-cocoa-and-cocoa-is>
- Gateau-Rey, L., Tanner, E.V.J., Rapidel, B., Marelli, J.P., Royaert, S. (2018). Climate change could threaten cocoa production: Effects of 2015-16 El Niño-related drought on cocoa agroforests in Bahia, Brazil. *PLoS ONE* 13(7).
- Huan, L. K., Yee, H. C. and Wood, B. J. (1986). Irrigation of cocoa on coastal soils in Peninsular Malaysia. In *Cocoa and Coconuts: Progress and Outlook*, Kuala Lumpur, Incorporated Society of Planters, 117–132.
- Kotei, R., Kyei-Baffour, N., Atakora, E. T. and Monney, I. (2016). Influence Of Change In Climate And Urban Characteristics On Hydraulic Designs And Drainage System In Mampong-Ashanti, Ghana. *ARNP Journal of Earth Sciences*. 5(2), 90 -99.
- Kotir, J. H. (2011). Limete Change and Variability in Sub-Saharan Africa: a review of current and future trends and impact on Agriculture and Food Security. *Environ. Dev, Sustain.* 13, 587-605.
- Läderach, P., Martinez, A., Schroth, G., Castro, N. (2013). Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire. *Clim. Chang.* 119, 841–854.
- Meteorological Service Agency (2007). Annual Report. Agriculture station, Mampong Ashanti.
- Michon, S. (2016). Climate and Chocolate. Available from internet, [tps://www.climate.gov/newsfeatures/climate-and/climate-chocolate](https://www.climate.gov/newsfeatures/climate-and/climate-chocolate) Retrieved June 6, 2017.
- Nieuwolt, S., Zaki Ghazall, M., and Gopina-Tham, B. (1982): *Agro-Ecological Regions in Penin-sular Malaysia*. M.A.R.D.I., Serdang. 20 pp.
- Mohr, H. and Schopfer, P. (1994). *Plant Physiology*. Springer Publishers, New York. Pp. 423 – 436.
- Odei, V. (1987). Business and finance „“Daily Graphic”“. Thursday December 3rd, 1998. Issue. P.7.
- Oyekale, A. S., Bolaji, M. B. and Olowa, O. W. (2009). “The effect of climate change on cocoa production and vulnerability assessment in Nigeria”. *Agricultural Journal*; 4 (2). 77-85.

Original Article

- Schwendenmann, L., Veldkamp, E., Moser, G., Holscher, D., Kohler M, Clough Y, et al. (2010). Effects of an experimental drought on the functioning of a cacao agroforestry system, Sulawesi, Indonesia. *Glob Change Biol.*; 16: 1515–1530.
- Vos, R., Velasco, M., Labastida, E. (1999). Economic and social effects of " El Nino" in Ecuador, 1997–8. *ISS Work Pap Series General Ser.* 292: 1–55.
- Wood, G.A.R., Lass, R.A. (2001). *Cocoa*, 4th Edition. .Blackwell Scientific, Oxford.
- Zuidema, P.A., Leffelaar, P.A., Gerritsma, W., Mommer, L. and Anten, N.P.R.. (2005). A physiological production model for cocoa (*Theobroma cacao*): model presentation, validation and application. *Agric Syst*; 84:195– 225.