PREDICTING SOIL WATER STATUS, EVAPOTRANSPIRATION, GROWTH AND YIELD OF YOUNG OIL PALM IN A SEASONALLY DRY REGION OF MALAYSIA

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ABSTRACT

The northern part of Kedah, Malaysia, generally experiences an annual dry season that may extend from two to three and a half months. Nevertheless, there has been increased expansion in the area of oil palm in the region. In this study, the model OPRODSIM (Oil Palm Production Simulator) was used to examine and predict responses to climatic conditions during the first six years after planting, based on daily climatic data, and to predict growth and yield for a further four years.

The mechanistic model generally confirmed measured trends in soil water status and crop water use, and effectively simulated annual bunch yields and annual changes in some vegetative parameters. It was least successful in reproducing frond production rate (FPR; mostly overestimated), frond biomass production (FBP; overestimated) and total frond number per palm (TFNP; either over- or underestimated except in the fourth year). Total vegetative standing biomass (TVSB), frond standing biomass (FSB) and trunk standing biomass (TrSB) were simulated well in years three and four but underestimated in the two subsequent years. Trends in root standing biomass were reproduced well.

Simulation of trunk biomass production (TrBP) was good, except in year six when it was underestimated. Root biomass production (RBP) was generally underestimated but simulation of total vegetative biomass production (TVBP) was generally satisfactory.

Bunch yields were well simulated, with the correspondence between mean measured and modelled yields being improved by lagging yield by two years with respect to the weather data.

These results suggest that the model provides a useful first approximation for simulating the effects of climate on yield, dry matter production, water use and soil water balance in a seasonally dry climate. However, improvements are necessary concerning the detailed simulation of vegetative growth.

Keywords: oil palm, dry season, soil water balance, evapotranspiration, growth and yield, simulation modelling.

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INTRODUCTION

The north of Kedah, close to the border with Thailand, is a region which in most years experiences two to three months of quite low rainfall. This dry season generally stretches from mid-December through to late March, during which time un-irrigated crops become very dependent on soil water reserves and ground water supplies. This is, therefore, a good area in which to study the effects of drought on oil palm growth and yield, the need for which has become more evident due to the current tendency to extend the planting of oil palm there.

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Previous investigations (Henson *et al*., 2005; Henson and Mohd Haniff, 2005; 2007) have described some of the short-term effects of drought on young oil palm in the area, with frequent measurements of vegetative growth and bunch yield being made, commencing respectively from the 30th and 32nd month after planting. Later work (Henson and Mohd Haniff, 2007), carried out from mid-December 2005 until the end of April 2006, when the dry season was interrupted at approximately monthly intervals by substantial rains, included continuous monitoring of the soil water status, as well as crop water use and canopy CO_2 and energy fluxes, over the four and a half-month period. However, some uncertainty regarding the soil water measurements suggested the need for a re-examination, which might be assisted by the use of modelling techniques.

A model can also be used to predict crop growth and yield. So, in addition to modelling soil water, the work was extended to cover crop growth and yield over the first six years from the time of planting, and to provide some predictions of yield and growth for future years. For this purpose use was made of OPRODSIM (Oil Palm Production Simulator[1]), a mechanistic oil palm simulation model under development at MPOB (Henson, 2005a). This provided an opportunity to test the performance of the model under quite challenging conditions.

MATERIALS AND METHODS

Site, Climate and Crop

Details of the experimental site (at Sintok, Kedah, 6.27° N, 100.29°E) are given in previous papers (Henson and Mohd Haniff, 2005; Henson *et al*., 2005;). The site is close to the border with Thailand where the monthly rainfall varies markedly during the year, with a minimum normally in January and February and a maximum, in October.

The oil palm stand was planted, following rubber, in July 2000 at a density of c. 148 palms ha^{-1} on c. 300 ha of a sandy clay loam of Batu Lapan series (Plinthic Hapludult, USDA classification). The soil had a calculated available water holding capacity (AWHC) in the top 1 m of c. 111 mm (Henson *et al*., 2005), based on 0.033 MPa soil water potential at field capacity. The monitored palms were un-irrigated.

For the purpose of monitoring crop growth, three plots of 16 palms (four palms x four rows) were used. In each plot, root samples and soil water measurements were each taken at two locations, one in an inter-row and one in a harvest path. These areas are referred to subsequently as sub-plots.

Climatic Data Sources

For modelling purposes, daily records of several meteorological variables were required from the month of planting. Detailed on-plot measurements of these commenced only in late October 2002, after installation of the necessary instruments and supporting structures. However, monthly rainfall records collected by the site Estate (Ladang ESPEK Tanjung Genting) were available from 1987 onwards (see Henson and Mohd Haniff, 2007 for data) and it was possible to derive daily values from these using a weather generating program (Mathews and Stephens, 1996), thus covering the period from planting in July 2000 up until late October 2002. The same approach was used to generate daily values of solar radiation (SRAD). The monthly mean SRAD data used were from the nearest Malaysian Meteorological Service station at Chuping, Perlis, (6.29° N, 100.16°E), approximately 25 km north-west of the site. Concurrent SRAD data from Chuping were found to be higher than the corresponding values at Sintok, and so the Chuping data were adjusted to allow for this.

Daily values for other climatic variables needed for the model (Tmin [daily minimum air temperature], Tmax [daily maximum air temperature], RHmin [daily minimum relative humidity], RHmax [daily maximum relative humidity], NRAD [daily total net radiation] and U [mean daily horizontal wind speed]), were obtained from SRAD using previously derived linear regressions (Henson, 2000; 2006a and unpublished).

On-Site Meteorological Measurements

Full details of the instrumentation at the site were as given in earlier papers (Henson and Mohd Haniff, 2005; Henson *et al*., 2005). The instruments provided continuous measurements of air temperature, atmospheric humidity, wind speed and direction, short-wave solar radiation, net radiation, photosynthetically-active radiation, soil water content (see below) and rainfall (some of this data being used to calculate potential evapotranspiration [PET], vapour pressure deficit [VPD] and other variables). For limited periods, concentrating on the dry season, the vertical exchanges of carbon dioxide, water vapour and sensible heat between the canopy and the atmosphere above were assessed by eddy correlation using a sonic anemometer and an open-path CO_2/H_2O gas analyzer (Henson and Mohd Haniff, 2005; 2007).

[1] See *Appendix 1* for full list of abbreviations.

Soil Water Measurements

Soil water content (SWC; $m^3\ m^{-3}$) was measured manually in each sub-plot at approximately monthly intervals from October 2002 using a Delta-T Devices (Burwell, UK) Profile probe as described earlier (Henson *et al.,* 2005).

A separate Profile probe was permanently installed in one of the sub-plots close to the meteorological recording instruments and its output recorded hourly using a data logger. The logger converted the probe voltage output to volumetric SWC using the calibration option for mineral soil supplied by the manufacturer. As previously described (Henson and Mohd Haniff, 2007), only the SWC at depths of 300 and 400 mm were well correlated with those obtained from mean manual readings at all positions, and they were considered useful only for indicating the relative changes and trends in SWC.

In May 2005, an additional system for measuring SWC (Minitrase 6050X3; SoilMoisture Equipment Corp., Santa Barbara, California, USA) was installed at the site. This uses the method known as time domain reflectometry (TDR) in which paired parallel steel rods (termed waveguides) of various lengths are inserted vertically into the soil, and to which an electromagnetic pulse is applied to measure the dielectric constant (SoilMoisture Equipment Corp, 2002). From this, the mean volumetric soil water content of the soil layer spanned by the rods can be calculated. The measurements were made using a mobile, battery-powered unit.

The waveguides were installed in circles surrounding the existing Profile probe access tubes as shown in *Figure 1*. Waveguides 1000 mm long were installed at 10 positions in each sub-plot, thus giving a mean SWC for the whole profile. At four positions

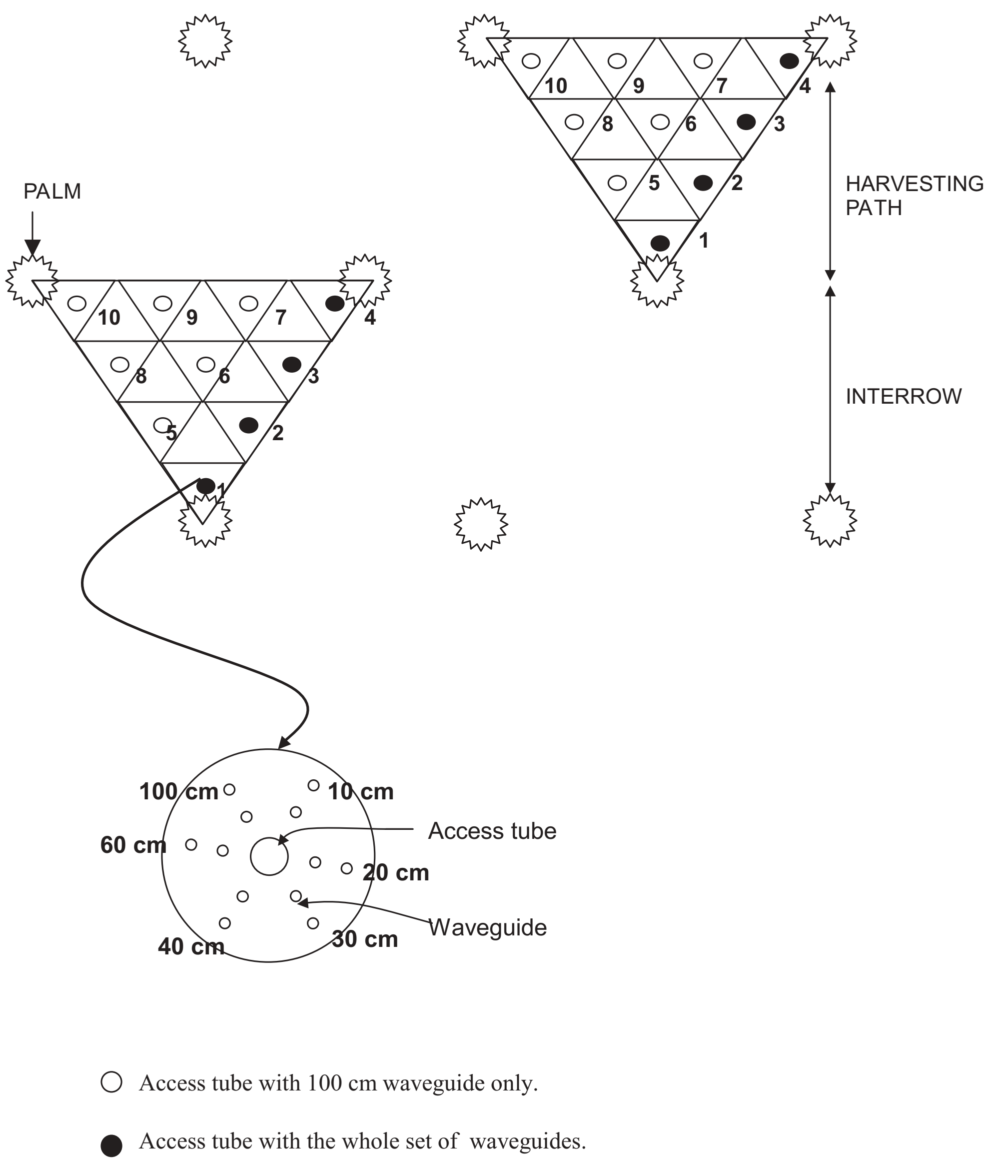

Figure 1. Schematic diagram of access tubes and waveguides placed in the field.

per sub-plot, additional waveguides, varying in length from 100 to 600 mm, were used to indicate the SWC at different depths. As with the Profile probe, readings were taken monthly, at about the same time.

Twelve months of output from the TDR system was regressed against that from the Profile probe, and the regression was used to calculate 'TDR-equivalent' values of SWC for previous months, starting from October 2002.

The estimates of soil water content were further checked gravimetrically, using soil cores taken to three successive 100 mm depths, one core per sub-plot, at three-monthly intervals beginning in June 2005.

Crop Measurements

The above-ground growth of the oil palm was assessed every six months from December 2002 (2.5 years after planting [YAP]) to June 2006, with an additional set of measurements being made in March 2006. The measurements were made on all palms in the three plots using conventional non-destructive techniques for assessing biomass (Hardon *et al*., 1969; Corley *et al*., 1971). Age-dependent corrections were applied to the leaf area and dry matter data as described by Henson (1993). The data permitted assessments of biomass from the end of the third YAP, with the third year based on a doubling of the preceding six month's growth.

Root standing biomass (RSB) was determined annually in December using an auger with samples taken to a depth of 0.9 m following the sampling system of Tailliez (1971), with 16 sampling points per triangular sub-plot (Henson and Chai, 1997). Root turnover was assessed six months later using the in-growth core method (Henson and Chai, 1997). Root biomass production (RBP) was taken as the sum of standing biomass increment and annual turnover.

The yield of fresh fruit bunches (FFB) was recorded bi-monthly or monthly with the number of bunches being counted and each bunch weighed in the field. The first bunches were harvested in February 2003 (32 months after planting).

Modelling of Growth, Yield, Soil Water Status and Evapotranspiration

The mechanistic simulation model OPRODSIM was run using the multi-year file option with the newly prepared climate files specific to the site, covering the first six years from planting. The general structure of the model is described by Henson (2005a) while further details of the soil water simulation can be found in Henson (2006a). Except where indicated, the standard parameter values listed in *Appendix 2* were used to run the model

To provide an indication of future trends, each run was extended four years beyond the measured date, *i.e.* up until 10 YAP. An additional climate file, representing average conditions, was used repeatedly for the additional years.

In order to lag the yield by one or two years with respect to climate, *i.e*. such that the yield in year n depends on the climate in year n-1 or n-2, the additional file was used for the first one or two years accordingly, being then followed in sequence by the year-specific files.

For checking results of the soil water measurements and to estimate crop evapo-transpiration, the model used the site AWHC of 111 mm and an age-dependent option for the factor VMOD, that determines vegetative responses to SWC (Henson, 2006b). The effects of increasing the AWHC by 50% (equivalent to an increase in effective rooting depth) were also explored.

RESULTS AND DISCUSSION

Soil Water Supply and Water Use

Large differences were found in the monthly measurements of soil water content between Profile probe and TDR data (*Figure 2a*), although the two were highly positively correlated (p<0.001). To check the validity of Profile probe and the TDR results, the water contents of soil cores were measured gravimetrically, with the soil cores being taken near to the probe positions. The results (*Figure 3*) clearly indicate that the probe data were too high while there was good agreement between TDR and gravimetric measurements.

To obtain long-term SWC data, the readings from Profile probes were adjusted using the linear relationship of *Figure 2b* to give 'TDR-equivalent' values. The estimates of SWC that resulted are compared in *Figure 4* with the values simulated by the model and with actual TDR values obtained from May 2005 to April 2006. The simulated data, which clearly indicate the annual dry periods and the extent to which they varied in different years, generally matched well the derived TDR data, with the two being highly significantly positively correlated (p<0.001).

Evapotranspiration by the crop was measured by eddy correlation (Henson and Mohd Haniff, 2005; 2007) over several months although the recording was not continuous due to instrumentation problems. The main results are shown in *Figure 5* where the long-term simulated values of both potential (PET) and actual evapotranspiration (AET) are compared with calculated/measured values. The PET values derived by the two methods differ, since whereas the model calculates PET daily from average daily data, the 'measured' values are based on hourly

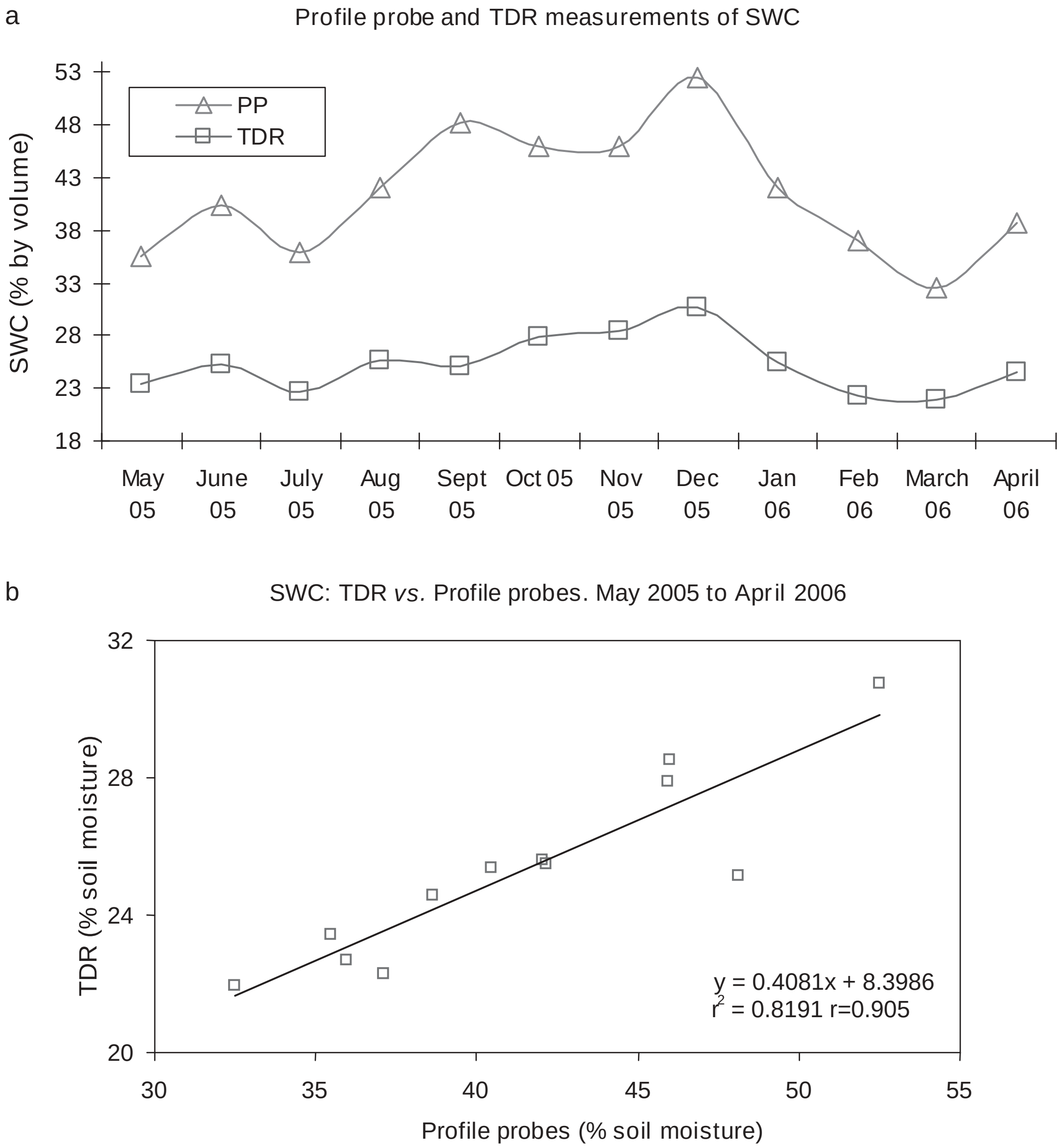

Figure 2. (a) Monthly estimates of volumetric soil water content (SWC) obtained using Profile probes and TDR equipment. (b) Regression of TDR data against Profile probe data of Figure 2a.

Notes: The data are means for the top 1000 mm of soil for readings taken at 10 positions in each of six sub-plots. Profile probe data for July 2005 are interpolated values.

readings of the determining climatic factors. The direct measurements of AET, though rather limited, agreed well with the simulated values, although in some months the latter were higher. (This was thought to be due to the EC sensors being at a height too low within the canopy boundary layer, resulting in the measured AET being too low.) The same pattern was evident for changes in the AET/PET ratio. The AWHC value used in the simulations had relatively little effect on AET or AET/PET (data not presented), although assuming 167 mm AWHC rather than 111 mm did result in some slightly higher AET values during drought periods.

Figure 6 shows results for the same period from mid-December 2005 to the end of April 2006 that was examined for crop responses as detailed in a previous paper (Henson and Mohd Haniff, 2007). In that report, changes in canopy gas exchange were related to rainfall and soil water status. Here, the simulated changes in AET and SWC are related to the measured values and to the rainfall. Although the same or similar patterns were evident for modelled and measured data, the former were often lower during the drier periods.

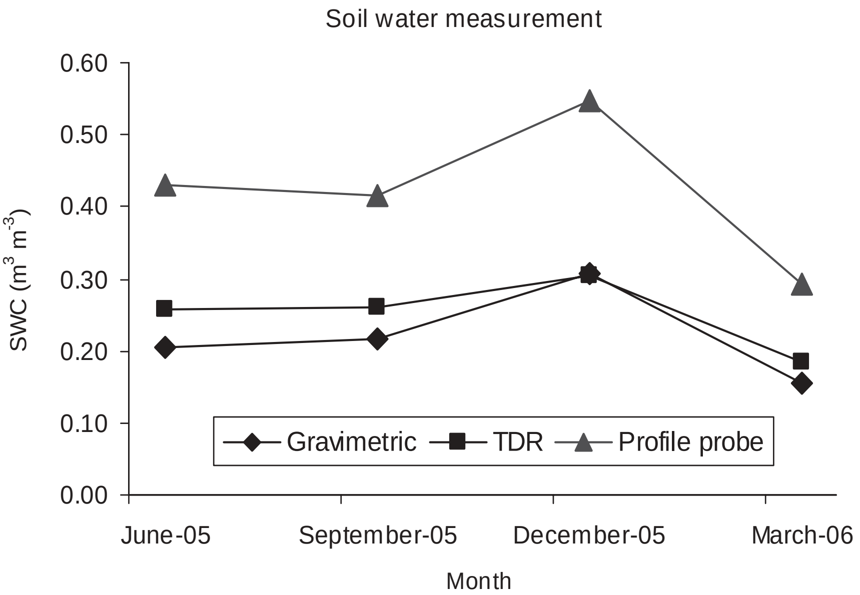

Figure 3. Volumetric soil water contents (SWC) obtained gravimetrically from soil cores, or using Profile probes or TDR equipment.

Notes: The data are means for the top three layers, each approximately 100 mm deep, using one soil core per sub-plot for the gravimetric sample and four positions per sub-plot for the probe and TDR measurements, with all six sub-plots sampled in all cases.

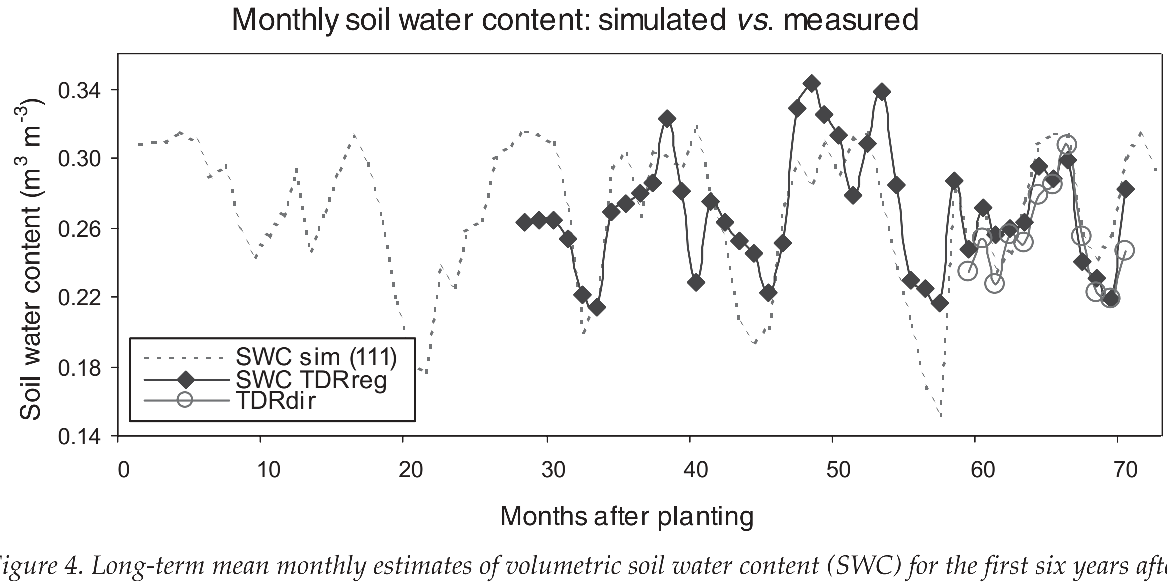

Figure 4. Long-term mean monthly estimates of volumetric soil water content (SWC) for the first six years after planting, produced by the model, compared with values measured directly using TDR equipment and TDR values generated by regression.

Notes: The model was run assuming an available soil water holding capacity of 111 mm. No comparative instrument data were available prior to 28 months after planting. The correlations between simulated SWC and TDR direct, and simulated SWC and TDR regressed values, were significant at $P<0.01$ and $P<0.001$, respectively.

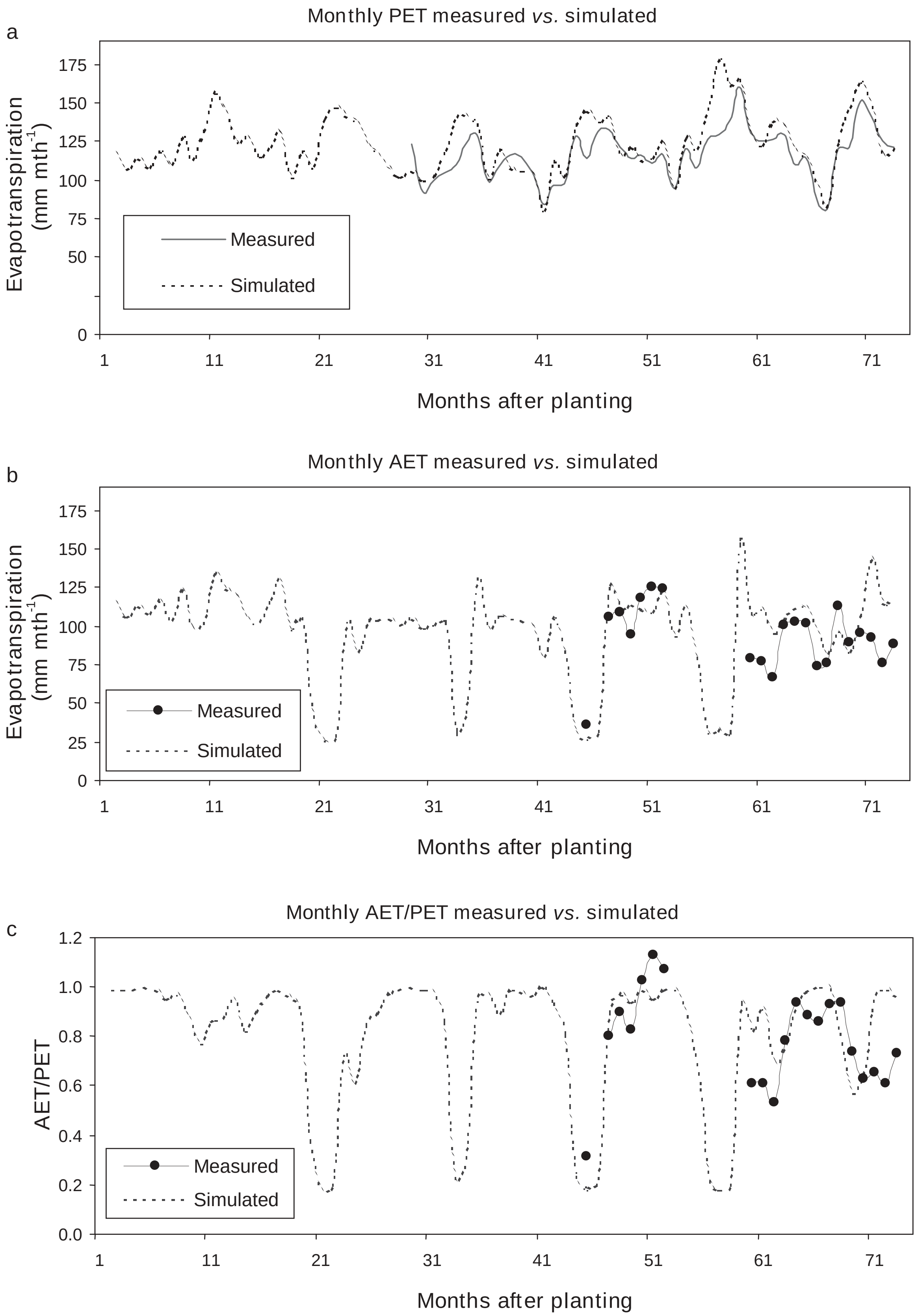

Figure 5. Long-term mean monthly simulations of (a) potential evapotranspiration (PET), (b) actual evapotranspiration (AET) and (c) the AET to PET ratio, compared with those obtained directly from micrometeorological measurements.

Notes: The simulations were run assuming an available soil water holding capacity (AWHC) of 111 mm. The correlations between simulated and measured values of PET, AET and AET/PET were significant at $P<0.001$, $P<0.01$and $P<0.001$, respectively.

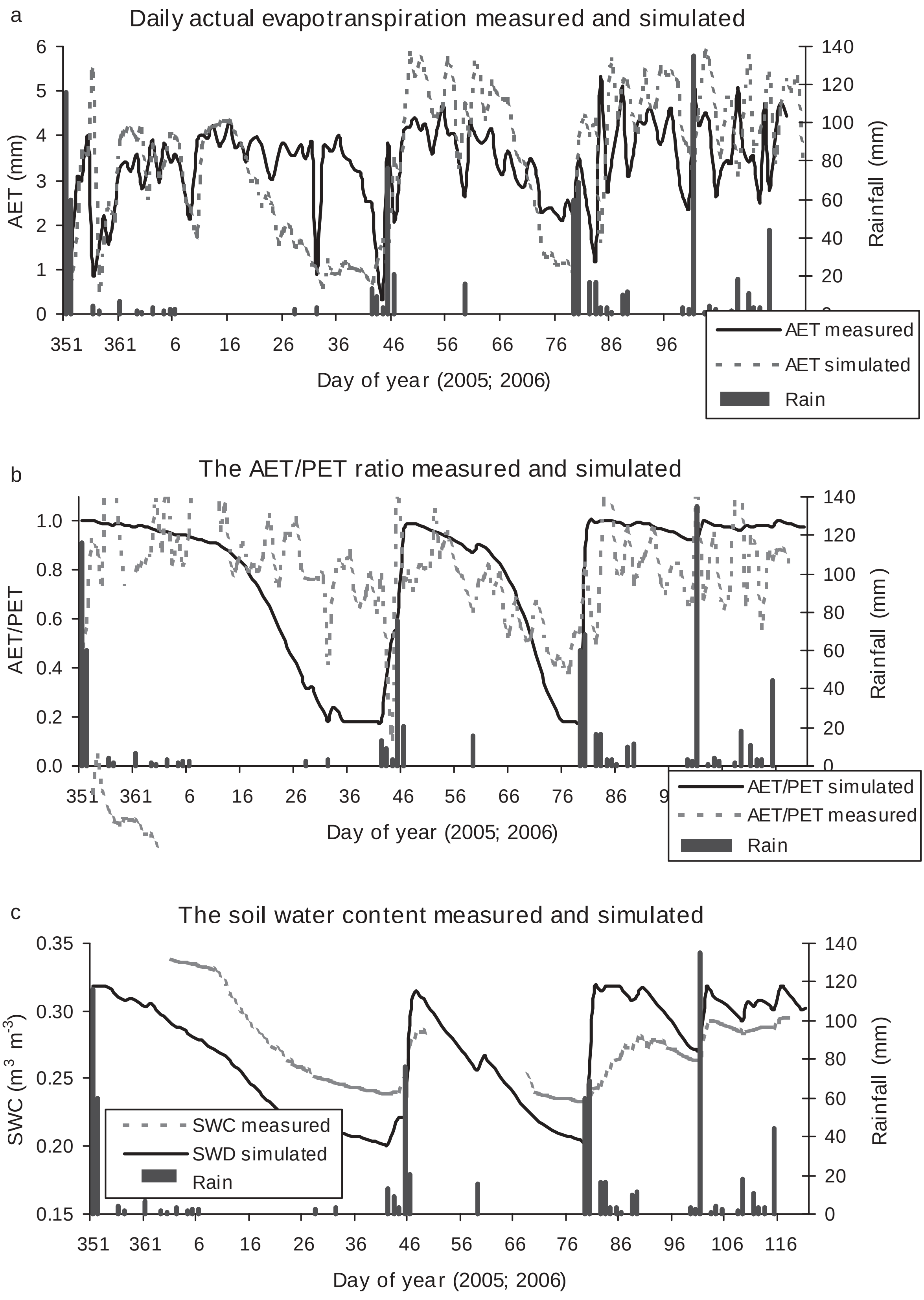

Figure 6. Daily changes in relation to rainfall events from mid-December 2005 to late April 2006 in (a) actual evapotranspiration, measured and simulated, (b) the actual to potential evapotranspiration ratio (AET/PET), measured and simulated, and (c) the soil water content (SWC), measured and simulated.

Notes: The simulations were run assuming an available soil water holding capacity of 111 mm. The 'measured' SWC was obtained using the regression equation given in *Figure 2b* applied to the continuous profile probe readings presented by Henson and Mohd Haniff (2007). The correlations between simulated and measured values of AET, AET/PET and SWC were all significant at $P<0.001$ with the number of paired data being 133, 131 and 114, respectively.

Crop Yield

Comparisons of measured and modelled annual FFB yields are shown in *Figure 7*. The time trends were similar and the simulated yields were often quite close to the real ones. Increasing the AWHC by 50% resulted in yields that were closer to those measured (*Figure 7a*) but it led to bigger differences between actual and modelled vegetative growth (see next section). Lagging yield with respect to climate so that yields were determined by the conditions prevailing either one or two years before, led to mean and cumulative yields that more closely matched the real ones, with the two-year lag and 111 mm AWHC giving the best agreement (*Table 1*). The rationale here is that conditions influence specific stages of inflorescence development and growth (specifically the stages of sex determination and of susceptibility to abortion) that long precede, yet determine, the bunch harvest. Such lag effects are normally not taken into account by the model, which calculates yield based only on the current assimilates available for bunch production, so ignoring developmental processes.

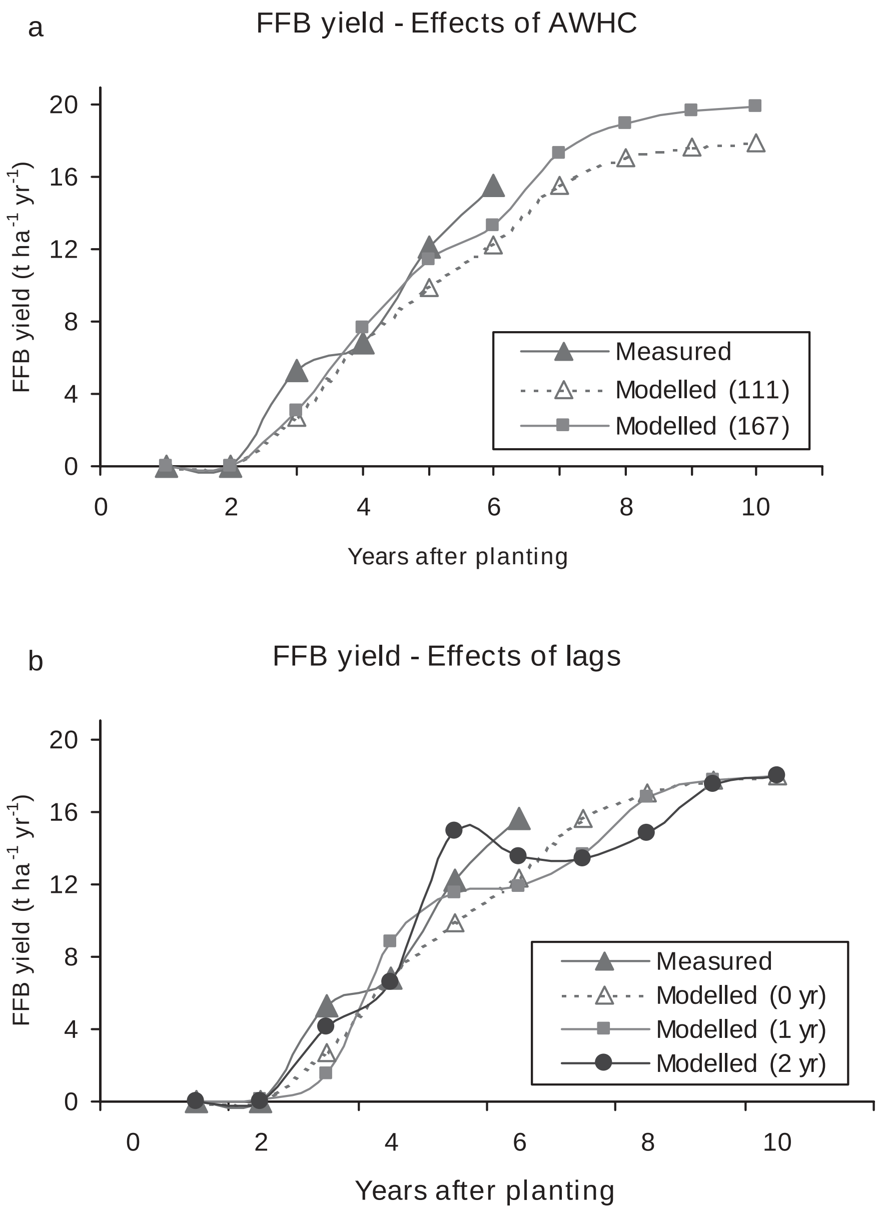

Figure 7. Comparisons of actual (measured) annual yields of fresh fruit bunches (FFB) with modelled yields.

Notes: In (a), actual yields are compared with modelled yields using two levels of available soil water holding capacity (AWHC), 111 and 167 mm. Yields were not lagged with respect to climate.
In (b), actual yields are compared with modelled yields with either a zero (0 yr), one (1 yr) or two (2 yr) year lag separating climate from yield, so that yields were dependent on the climate of either the current year, the preceding year, or the year two years earlier. Simulations were run using an AWHC of 111 mm.

TABLE 1. TOTAL YIELD OF FRESH FRUIT BUNCHES (FFB) RECORDED IN THE TRIAL DURING THE FIRST SIX YEARS AFTER PLANTING, COMPARED WITH SIMULATED YIELDS *

	Lag period	AWHC**	Cumulative FFB yield	
		mm	t ha^{-1}	% of actual yield
Measured	-	111	39.85	100
Modelled	None	111	31.65	79.4
		167	35.51	89.1
	1 year	111	33.83	84.9
		167	37.86	95.0
	2 years	111	39.17	98.3
		167	43.38	108.9

Notes:
* The standard option in the model for simulating vegetative growth (*Appendix 2*) was used in all cases.
**Available soil water holding capacity.

The monthly FFB yields are shown in *Figure 8*. These show large seasonal variation with minimum yield during the dry seasons. However, the pattern thus far is rather irregular with a tendency for yield peaks to be bi-modal, indicating the complex nature of the cycles. Since, as stated above, the model takes no account of climatic impacts on developmental processes (such that yield is solely determined by assimilate supply), it is unlikely that the detailed seasonal variation would be adequately reproduced. However, there was some correspondence between the observed and modelled yield patterns, with a slightly better agreement, as shown by correlation analysis, using the un-lagged yield.

Crop Vegetative Growth

In assessing the results of modelling growth, it is useful to examine the sub-components to identify which aspects deviate most from actuality. *Figure 9* compares the measured, with simulated values of total frond number per palm (TFNP), leaf area index (LAI), single frond dry weight (SFDW) and frond production rate (FPR). The model was run with two values of AWHC, but this generally had very little effect. For LAI and SFDW, the modelled results are very close to those measured in the fifth and sixth year, but deviate from them in the earlier years. This might be due to the values measured being over-corrected for the age effect, since the corrections factors used (Henson, 1993) were derived from measurements at other sites, and might differ with the planting material and environment. For TFNP and FPR, only the values in the fourth year agreed well with the real data. TFNP was otherwise both over- and underestimated in the model. The higher frond numbers found in the real palms indicate restricted pruning, as the FPR (the other determinant of TFNP) was generally lower than anticipated. The low pruning rate probably arose from the bunch number being lower than is normal for most stands. Thus, over the four years of measurement, bunch number per palm averaged only 10.4, while the mean FPR, (which sets the upper limit to bunch number) was 25.6 giving a bunch/frond ratio of 0.4, while values over 0.8 have been observed for palms at the same ages on more productive sites.

Nevertheless, as shown by the LAI data, the effects of the discrepancies in TFNP and FPR were not necessarily very great, although they were important in determining FSB and FBP (see below).

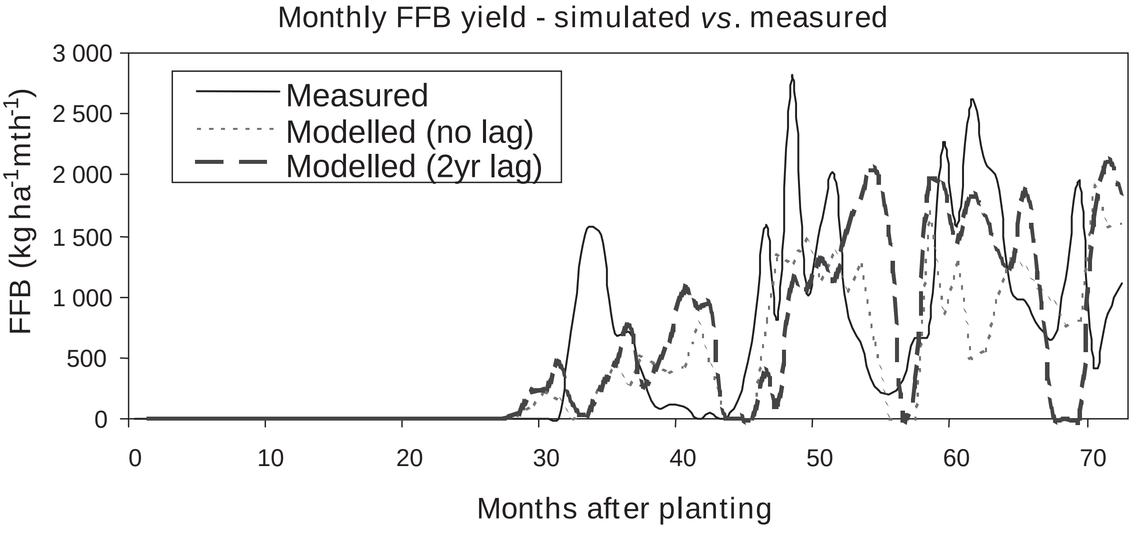

Figure 8. Comparison of actual (measured) monthly yield of fresh fruit bunches (FFB) with modelled yields, the latter unlagged or with a two-year lag with respect to climate.

Notes: Yields were modelled assuming an AWHC of 111 mm. The correlations between simulated and measured yields for the period commencing 28 months after planting (first modelled yields) with and without a lag, were significant at $P<0.05$ and $P<0.02$, respectively.

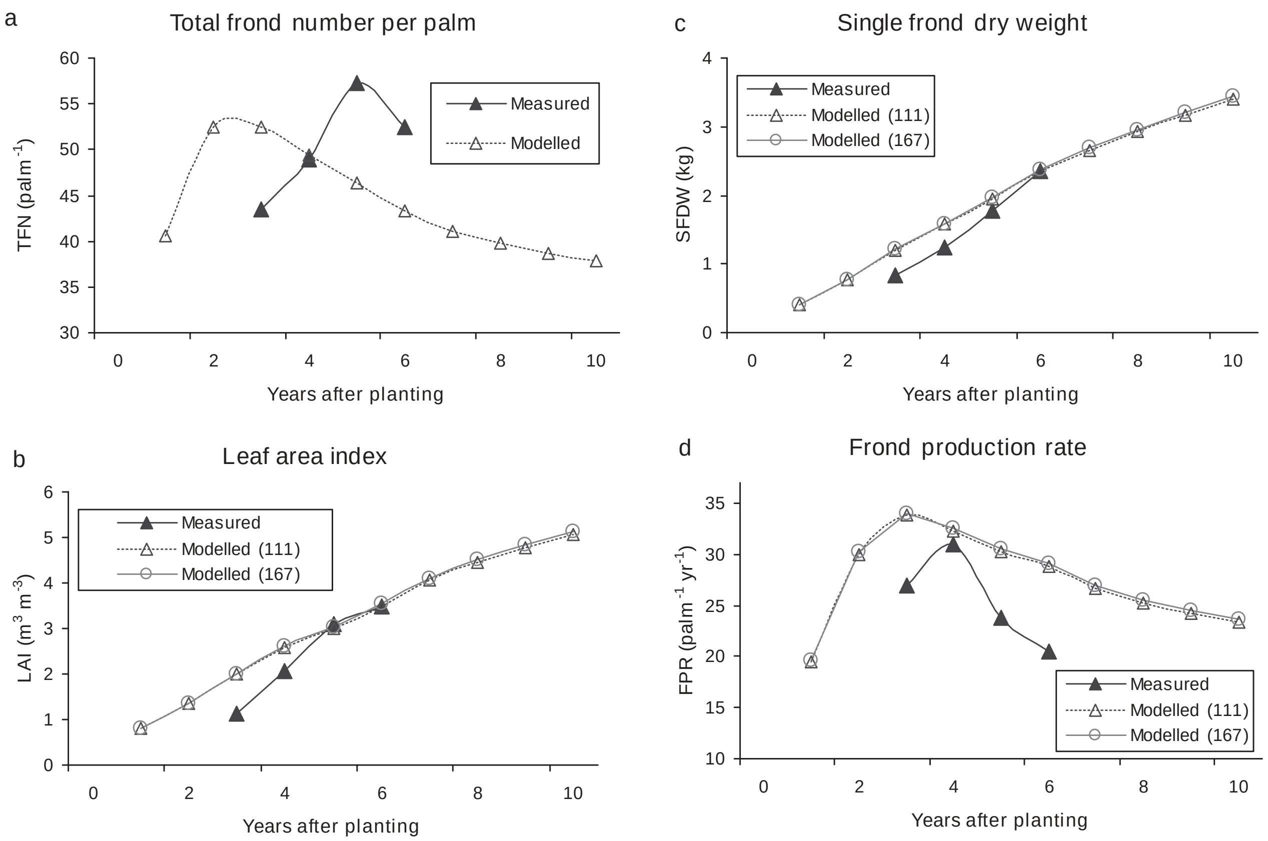

Figure 9. Comparisons between actual (measured) and modelled values of some primary palm growth variables.

Notes: Numbers in brackets for modelled data refer to the available water holding capacity of the soil (mm). This parameter had no effect on total frond number, hence, for that, only one modelled curve is presented.

The dry matter production of the main palm parts is illustrated in *Figure 10a.* The model overestimated FBP (mainly due to overestimation of FPR) and underestimated RBP in all years, but with the exception of year six, trunk growth was reasonably well simulated. Total TVBP (*Figure 10b*) was underestimated by the model in most years, but the differences from measured values were small.

The standing biomass (SB) was initially well estimated by the model (*Figure 11*), but as time went by it was progressively underestimated. The largest discrepancy occurred with the fronds (since these were the largest component of standing dry matter) but the same trends were apparent for trunk and roots also.

The relationships between measured and modelled vegetative production and standing biomass are summarized in *Table 2*. The simulation of TVBP and TVSB was poorer than that of bunch yield.

While mean bunch yields could be simulated to within less than 2% of measured values allowing a two-year lag (*Table 1*), lagging was not considered necessary in the case of vegetative growth as this is expected to respond more or less immediately to changed conditions. This is shown, for example, by

TABLE 2. MEAN ANNUAL TOTAL VEGETATIVE BIOMASS PRODUCTION (TVBP) AND VEGETATIVE STANDING BIOMASS (TVSB) FOR THREE TO SIX YEARS AFTER PLANTING, RECORDED IN THE TRIAL COMPARED WITH SIMULATED VALUES *

	AWHC **	TVBP		TVSB	
	mm	t ha^{-1} yr^{-1}	% of actual	t ha^{-1}	% of actual
Measured	111	9.64	100	19.29	100
Modelled	111	10.48	108.7	16.00	82.9
	167	11.05	114.6	16.15	83.7

Notes:
* The standard option in the model for simulating vegetative growth was used in all cases.
** Available soil water holding capacity.

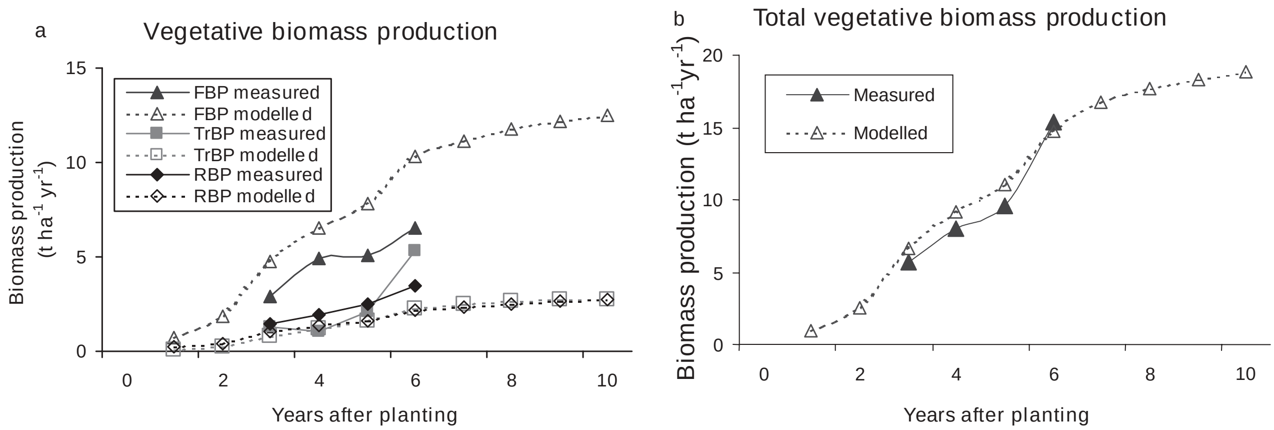

Figure 10. Comparisons between actual (measured) and modelled values of vegetative biomass production.

Notes: In (a), individual organ data are shown while (b) contains the total values. The modelled data were obtained using an AWHC of 111 mm. See *Appendix 1* for explanation of variable names.

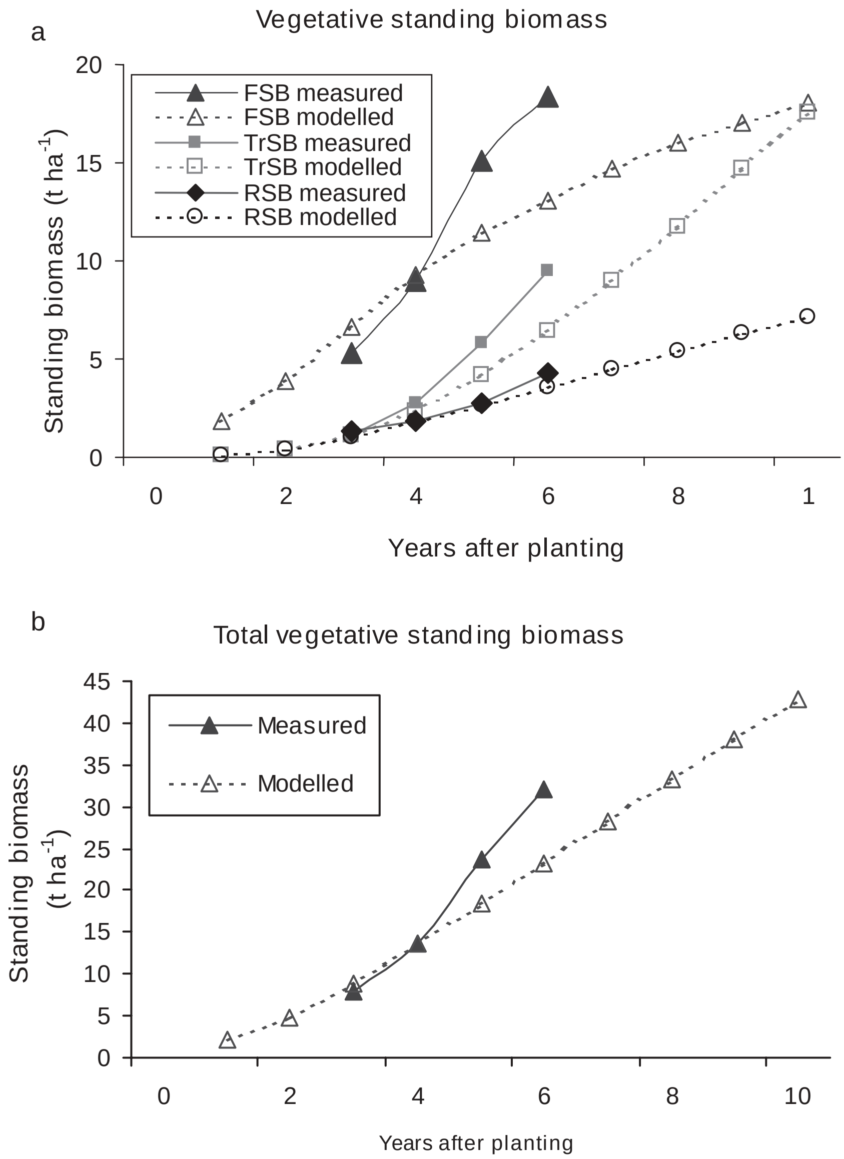

Figure 11. Comparisons between actual (measured) and modelled values of standing vegetative biomass.

Notes: In (a), individual organ data are shown while (b) contains the total values. The modelled data were obtained using an AWHC of 111 mm. See *Appendix 1* for explanation of variable names.

the rapid changes in spear leaf extension rate (Henson, 1991; Henson *et al*., 2005) and the inhibition of frond expansion that result in spear leaf accumulation, which accompany droughts. However, from the same runs of the model that resulted in the un-lagged yield data of *Table 1*, even the best estimates of vegetative growth (*Table 2*), were only within 17% of the measured values.

Adjustment of Model Parameters to Optimize Model Output

Reducing FPR by 18% led to quite precise estimates of TVBP using an AWHC of 111 mm, but TVSB was then reduced by 28%, and bunch yield by 43% below their actual values. Increasing TFNP improved TVSB but led to greater overestimates of TVBP. Combining both adjustments resulted in a compromise but with TVSB still being too high and TVBP too low, while bunch yield was still underestimated. These trends were similar irrespective of AWHC.

All the above tests used the standard method of simulating TVBP (Henson, 2006b) where TVBP is a function of LAI. This means that increasing TFNP, which will tend to increase LAI, automatically leads to an increase in TVBP, which, in this instance, was unwanted. Hence, further tests were run using the alternative method, which generates TVBP from FBP based on SFDW and standard trunk and root growth curves.

The effects on vegetative growth and yield were then examined, of increasing the maximum light-saturated photosynthesis rate or AMAX (the main variable leaf photosynthesis parameter), with and without the use of a two-year lag with respect to climatic conditions. Increasing AMAX increased the bunch yield while having much less effect on vegetative growth (which has first call on assimilates). As shown in *Table 3*, an increase in AMAX by some 39% above the default value of 18 µmol CO_2 m^{-2} s^{-1} was, however, required to match the modelled with the measured bunch yield (after also increasing TFNP and reducing FPR in order to achieve more realistic vegetative growth). This rather high AMAX could be reduced, and similar yields obtained, if a two-year lag was introduced (*Table 3*). A lower AMAX also sufficed when AWHC was increased from 111 to 167 mm.

While average modelled and measured values could be quite close using optimum or near-optimum parameter values, the data for individual years agreed less closely (*Figure 12*). Thus, the measured TVSB was less than that simulated in the first two years of measurement but the reverse was the case in the next two years. For FFB, the opposite trends were observed.

These exercises do not necessarily establish correct values for the model parameters. However, they do indicate the potential for the model to simulate the major variables given appropriate inputs. The difficulty remains in the need to determine the parameter levels that operate in the field and how they might change with time.

Potential Yields with Irrigation

The model can also be used to predict the yields possible with sufficient irrigation. Thus far, irrigation at the site has been unsuccessful in that irrigated plots have produced similar yields and yield patterns to un-irrigated control plots, largely due to inadequate water being applied (Henson, 2005b). With an effective level of irrigation substantial yield gains might be possible, as reported in previous studies (Corley, 1996). Some predictions obtained using the irrigation option of the model (Henson, 2006c) are presented in *Table 4*.

TABLE 3. PARAMETER VALUES AND SETTINGS REQUIRED TO RECONCILE MODELLED VEGETATIVE GROWTH AND BUNCH YIELDS WITH MEASURED VALUES *

Test	Variable inputs **			Outputs+					
	Lag	AWHC	AMAX	TVSB		TVBP		FFB	
	yr	mm	µmol m^{-2} s^{-1}	t ha^{-1}	% of actual	t ha^{-1} yr^{-1}	% of actual	t ha^{-1}	% of actual
1	0	111	25.0	19.31	100.6	9.06	94.0	39.75	99.7
2	2	111	18.0	19.44	100.8	9.04	93.8	23.85	59.9
3	2	111	22.5	19.44	100.8	9.20	95.4	40.09	100.6
4	2	167	21.0	19.55	101.3	9.51	98.7	39.03	97.9

Notes:
* The alternative option for simulating vegetative growth in the model was used in all cases. Total frond number per palm was increased by 13% and frond production rate was reduced by 22% of standard values.
** Lag refers to the interval between the climatic conditions and modelled responses; AWHC is the available soil water holding capacity; AMAX, the light-saturated rate of leaf photosynthesis.
+ TVSB is the total vegetative standing biomass; TVBP, the total vegetative biomass production and FFB, the fresh fruit bunch yield. TVSB and TVBP are averages from the third to sixth year after planting while FFB is the total for the first six years after planting.

TABLE 4. MEAN SOIL WATER DEFICIT (SWD) AND TOTAL YIELD OF FRESH FRUIT BUNCHES (FFB) PREDICTED BY THE MODEL DURING THE FIRST SIX YEARS AFTER PLANTING, WHEN IRRIGATING TO FIELD CAPACITY AT DIFFERENT SWD THRESHOLDS, COMPARED WITH THOSE RECORDED IN THE TRIAL*

	SWD irrigation threshold	Irrigation applied	Mean daily SWD	Cumulative FFB yield	
	mm	mm yr^{-1}	mm	t ha^{-1}	% of actual yield
Measured	-	0	49.2	39.85	100
Modelled	100	270	14.7	48.29	121.2
	50	522	10.3	59.55	149.4
	25	658	7.5	62.50	156.8
	5	929	3.6	64.78	162.6

Note:
*The 'threshold' method of irrigation scheduling was used (Henson, 2006c), in which irrigation is applied to restore SWC to field capacity when a selected level (threshold) of SWD is reached. An AWHC of 111 mm was assumed.

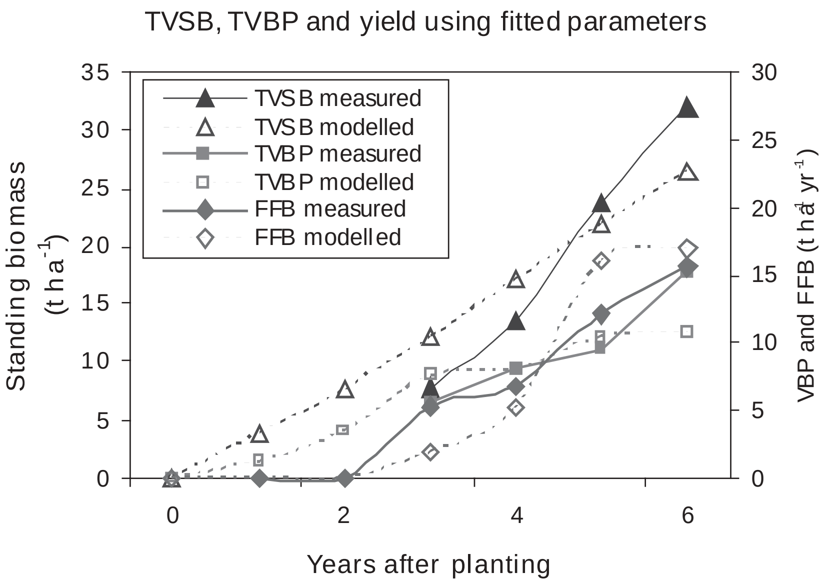

Figure 12. Comparisons between actual (measured) and modelled values of total standing vegetative biomass (TVSB), total vegetative biomass production (TVBP) and fresh fruit bunch yield (FFB), using fitted parameter values in the model.

Notes: The following parameter values/conditions were used in running the model: method of simulating TVBP, alternative; climate lagged by two years; FPR increased (x 0.78); TFNP increased (x 1.13); AWHC, 111 mm; AMAX, 22.5 µmol m^{-2} s^{-1}.

CONCLUSIONS

Modelling the growth of any crop and the changes in its environment presents a strenuous test of our understanding of the underlying crop physiological mechanisms. This is particularly so with a perennial, the yield of which is a result of a long period of development (possibly several years) during which conditions will vary.

While some of the data are fragmentary, they do indicate that the model is able to adequately simulate most processes, so offering a means of extending and supporting direct measurements, which are often difficult to make either with sufficient frequency (*e.g.*, soil water content) or over sufficiently protracted periods (*e.g.*, canopy gas and energy flux measurements).

During the study, large discrepancies were found between methods of measuring soil water content. It was evident, using the gravimetric method as the standard, that the TDR method was giving more accurate values of SWC than the Profile probes, which substantially overestimated the water content. The modelled data were generally in good agreement with the TDR. This indicates that previous assessments of drought-induced declines in the ASWC at the site using the Profile probe (Henson and Mohd Haniff, 2005; Henson *et al*., 2005), were very likely underestimates. Profile probes are known to suffer from inaccuracies arising from soil salinity or from air gaps developing between the access tube and the soil, but neither of these is likely to explain the present data, mainly because both factors would tend to reduce, rather than increase, the measured SWC (Delta-T Devices, 2001). Also, air gaps are unlikely under the wet conditions that prevailed over much of each year.

If the model is validated further by future observations, particularly those of yield, then the full history of the soil water status that it provides can be further related to growth and yield of the crop, and perhaps provide a means of yield forecasting. Greater understanding of the effects of water supply on yield-determining processes (sex determination, inflorescence abortion) based on inflorescence counts, analysis of which is underway, should assist with this.

The model can also be used to predict the yields possible with full irrigation, although this aspect has yet to be fully validated. Thus far, attempts at irrigation at the site have been unsuccessful, largely due to the water applied being grossly insufficient (Henson, 2005b), with irrigated plots producing very similar yields and yield patterns to control plots, With proper irrigation practice, substantial yield gains should be possible.

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Appendix 1

LIST OF ABBREVIATIONS USED IN TEXT

AET	Actual evapotranspiration
AMAX	Light-saturated rate of leaf photosynthesis
AWHC	Available soil water holding capacity
FBP	Frond biomass production
FFB	Fresh fruit bunch
FPR	Frond production rate
FSB	Frond standing biomass
LAI	Leaf area index
NRAD	Net radiation
OPRODSIM	Oil Palm Production Simulator
PET	Potential evapotranspiration
RBP	Root biomass production
Rhmax	Maximum daily relative humidity
Rhmin	Minimum daily relative humidity
RSB	Root standing biomass
SB	Standing biomass
SFDW	Single frond dry weight
SRAD	Short-wave solar radiation
SWC	Volumetric soil water content
SWD	Soil water deficit
TDR	Time domain reflectometry
TFNP	Total frond number per palm
Tmax	Maximum daily air temperature
Tmin	Minimum daily air temperature
TrBP	Trunk biomass production
TrSB	Trunk standing biomass
TVBP	Total vegetative biomass production
TVSB	Total vegetative standing biomass
U	Horizontal wind speed
VBP	Vegetative biomass (dry matter) production
VMOD	Factor relating vegetative growth to soil water content
VPD	Atmospheric vapour pressure deficit
VSB	Vegetative standing biomass
YAP	Year after planting

Appendix 2

OPRODSIM STANDARD PARAMETER VALUES AND CONDITIONS USED IN MODEL RUNS AS PRODUCED BY THE PARAMETER LISTINGS FILE*

```
Programme: OPRODSIM [version OPRODS16A] Last revised 29 July 2006
Annual dry matter production and yield model
********** ****** ********** ********* *****
RUN Name or number: 1
DATE of run: 08-04-2006 (M:D:Y)  TIME: 15:02:04
SIMULATED CONDITIONS:

1.  SITE and CLIMATE:
    Seasonally dry
    Multi-year climate file used

2.  PLANTING INFORMATION:
    Year of planting: 2000
    Day of year of planting: 182
    Initial planting density: 148 per ha.

3.  CANOPY CHARACTERISTICS:
    PAR Extinction coefficient=  .47
    Qyield = 55 mmol CO2/mol PAR
    AMAX = 18  µmol CO2/m2/s
    Gross assimilation averaging period = 1  day(s)

4.  VEGETATIVE GROWTH SIMULATION:
    Vegetative growth simulation based on LAI
    Age-dependent TVBP partition ratios
    Medium frond size option
    Trunk height independent of biomass

5.  IDEOTYPE TESTS:
    TVBP partitioning unchanged
    Root turnover fraction unchanged.
    Specific leaf area ratio equation unchanged
    Frond production rate unchanged
    Medium trunk height growth rate
    Bunch development time 150 days

6.  CLIMATIC FACTORS affecting production:
    Radiation only

7.  MANAGEMENT OPTIONS:
    No management options were exercised

8.  SOIL WATER BALANCE SIMULATION (INLAND OR DRY SITE):
    AWHC constant at: 111  mm
    VMOD age-dependent

9.  RADIATION REGIME SIMULATION:
    No change in RADIATION REGIME simulated

10. CLIMATE CHANGE OPTIONS:
    No climate change option selected
```

*For further details, see Henson (2005a).