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MODELLING SEASONAL VARIATION IN OIL PALM BUNCH PRODUCTION USING A SPREADSHEET PROGRAMME

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ABSTRACT

Annual cycling in oil palm bunch yield is an almost invariable phenomenon even in regions that lack marked seasonal changes in climatic factors, such as radiation or rainfall, likely to have a large influence on yield. Furthermore, such cycles persist even under irrigated conditions. While yield-based endogenous feedback mechanisms have been invoked to partly account for such behaviour, the likely time-lags involved are not generally consistent with the regular annual cycles that are frequently observed.

Using data obtained from a long-term trial on a peat soil with a good year-round water supply, the role of various developmental factors in contributing to the resultant yield patterns, was examined. The factors were: a) frond emergence interval (FEI), b) rate of inflorescence and bunch development (FEBR; defined by the number of days from frond emergence to bunch ripening), c) the proportion of nodes with bunches (NWB; mainly a function of sex ratio and abortion incidence) and d) single bunch weight (SBW). Frond emergence, male and female inflorescence numbers, abortion and single bunch weight all exhibited regular annual variation in the trial.

Yields were simulated using a spreadsheet with the aim of dissecting out the contribution and relative significance of each factor. Even with all factors held constant, there was variation in monthly yield, although it was erratic and failed to result in the single annual peak characteristic of observed yield patterns. Regular annual peaks were, however, obtained by introducing sinusoidal oscillations in the amplitudes of the four factors either individually or in combination. Amplitudes were tested that represented a range of probable behaviour from mild to maximum variation. The best agreement between simulated and observed yields over an 8.5-year period (r^2=0.6) was obtained by varying NWB (using an amplitude of 50%) while similarly good agreements were achieved by appropriate variations in FEI and in FEBR. SBW had only a small effect.

Combining factors did not appreciably improve the correlations over those obtained by the factors individually, although in some cases it resulted in similarly high correlations being achieved using lower amplitudes.

These findings show that all the developmental processes examined played some role in accounting for annual yield cycles but the results still leave open the question of what factor(s) are responsible for the cycling of each of the underlying processes.

Keywords: oil palm, seasonal yield variation, developmental cycles, simulation model.

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INTRODUCTION

Seasonal cycles (generally single peaks with annual periodicity) are a characteristic feature of yield behaviour in oil palm (Corley, 1977) and underpin the monthly variation in palm oil production found in different producing counties. Large seasonal variation is not unexpected in regions such as West Africa, where regular and quite severe annual dry seasons are common (Corley and Tinker, 2003). However, similar though less extreme cycles in palm oil production are also evident in the much more uniform climates of Southeast Asia and the Pacific region (Chow, 1992). Furthermore, they persist even

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when periods of severe soil water deficit are minimized or absent due either to irrigation or the presence of permanent ground water within the rooting zone (Chan *et al*., 1985; Kee and Chew, 1993; Foong and Lee, 2000).

It has been argued that yield cycling in the absence of marked external constraints is a consequence of opposing effects of current, on future, yield (Breure and Corley, 1992; Corley and Breure, 1992). Such endogenous mechanisms could operate independently of external conditions. Current yield level is considered to impact most on events determining future bunch number (sex ratio, abortion). However, the time lags involved in these processes would not readily lead to regular 12-month yield cycles unless abortion levels were high and sex differentiation occurred at a relatively late stage (Henson and Jones, 2005).

Variation in several developmental processes could contribute to cycles in fruit bunch production in oil palm. These include the rate of frond emergence (Chang *et al*., 1988), the inflorescence development rate both before and after frond emergence, the rate of bunch development after anthesis, and factors such as pollination efficiency that affect bunch weight. While the general nature of each of these factors has been described, the extent to which they might contribute individually to the final yield pattern has not been determined. The purpose of the present work was to examine to what extent seasonally-related variation in the main underlying developmental processes could influence cycling in yield measured on a monthly basis.

BASE DATA AND YIELD SIMULATION

The simulations were based on data sets obtained from an oil palm density trial planted on a peat soil at MPOB Peat Research Station, Teluk Intan, Perak (Henson and Mohd Tayeb, 2003; 2004). The site had a permanent water table within range of the root system and an adequate well distributed rainfall. Nevertheless, the annual yield cycles were very regular and pronounced and highly synchronised across planting densities (Henson and Tayeb, 2004). The data used were those for the medium density treatment of 160 palms ha^{-1} and included monthly records of bunch yield, bunch number and mean bunch weight, quarterly records of frond production, male and female inflorescence production and abortion, and annual vegetative measurements. Data were available from the second half of the third year after planting (YAP) to the first half of the 17th year.

From an examination of the quarterly data (*Figure 1*), two periods of development can be distinguished. During the first period, up until the ninth YAP, mean rates of frond and inflorescence production steadily declined. After that time, relatively stable linear trends were established for these attributes. During both phases, there were regular annual oscillations in all the variables. In order to simplify the analysis, simulations were confined to the second, more stable period.

Annual means of the main variables used in the analysis are given in *Table 1*. It should be noted that while yields were simulated only from the ninth YAP, because of lags, the previous year's data for frond production were also required.

Simulated yields were calculated from simulated bunch numbers and weights. Timing of yields depended on the date of frond emergence and the interval between frond emergence and bunch ripening (FEBR).

To simulate cycles in the frond emergence interval (FEI), in the proportion of nodes with bunches (NWB; from which bunch number was derived) and in single bunch weight (SBW), sinusoidal curves

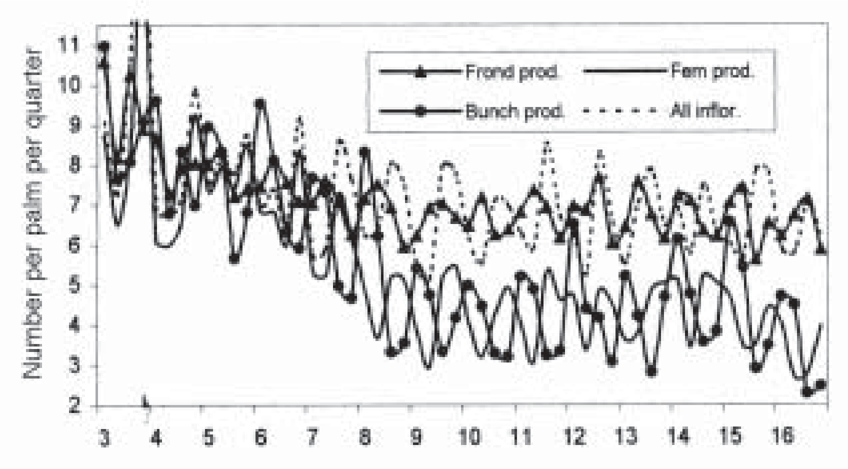

Figure 1. Quarterly changes in the production of fronds, total inflorescences, female inflorescences and fruit bunches at 160 palms ha^{-1} in the density trial used as the standard reference data set.

TABLE 1. ANNUAL DATA FROM THE DENSITY TRIAL FOR 160 PALMS PER HECTARE

Years after planting	Frond production per palm per year	Bunch number per palm per year	Mean bunch weight (kg)	FFB yield ($t\ ha^{-1}\ yr^{-1}$)
8	28.0	24.2	8.16	31.5
9	26.0	17.0	9.73	26.5
10	27.4	16.9	10.38	28.1
11	26.8	16.6	11.24	29.8
12	26.9	17.5	11.54	32.3
13	27.7	16.7	11.29	30.1
14	27.2	18.4	12.51	36.8
15	27.0	19.4	12.29	38.1
16	25.1	15.5	13.39	33.3
Mean	26.9	18.0	11.17	31.8

were generated with annual oscillations of varying amplitude. The amplitudes were chosen as representing low, medium and high values for each simulated character. FEI and NWB were calculated from the trial quarterly data while SBW was available from monthly harvest records. FEBR was not recorded in the trial and the likely variation in this factor was based on previous studies (Chang *et al*., 1993; 1995; Lamade *et al*., 1998).

Correlation coefficients between simulated curves and observed ones were then calculated (*Table 2**) to check the appropriateness of the curves in terms of both phase and amplitude. The best matches were obtained by offsetting simulated values by minus one-quarter of a year against observed (*Figure 2*).

For FEI and SBW, the cyclical variation in each was superimposed on the linear trend (*Figure 2*), though the trend was quite small in the case of FEI.

Simulation of yield was carried out as follows. Firstly, taking 1 January 1993 as day 1, the FEI was used to calculate the day of emergence of each frond. Either the mean FEI was used (*i.e.* averaged over years), or it was increased linearly using a regression on cumulative node number, or it was varied cyclically assuming an annual sinusoidal oscillation. The cyclical variation was superimposed on the linear trend (*Figure 3*).

TABLE 2. CORRELATION COEFFICIENTS BETWEEN OBSERVED (real) AND SIMULATED QUARTERLY CHANGES IN FROND EMERGENCE INTERVAL, PERCENTAGE OF NODES WITH BUNCHES AND SINGLE BUNCH WEIGHT

Factor	Amplitude	Units	Lag time (quarters)				
			2	1	0	-1	-2
Frond emergence interval	0.5	days	-0.21	-0.64	0.27	**0.60**	-0.32
	2.0		-0.30	-0.65	0.37	**0.58**	-0.40
	4.0		-0.30	-0.65	0.37	**0.58**	-0.40
% Nodes with bunches	10	%	0.61	-0.68	-0.58	**0.69**	0.61
	25		0.61	-0.68	-0.58	**0.69**	0.61
	50		0.61	-0.68	-0.58	**0.69**	0.61
Single bunch weight	0.5	kg	0.63	0.52	0.71	**0.82**	0.69
	1.0		0.53	0.32	0.62	**0.83**	0.60
	2.0		0.33	0.03	0.45	**0.75**	0.41

Note: Maximum positive correlations (all significant at $p<0.001$; $n=30$) shown in bold, were obtained by lagging simulated, with respect to observed values, by one-quarter.

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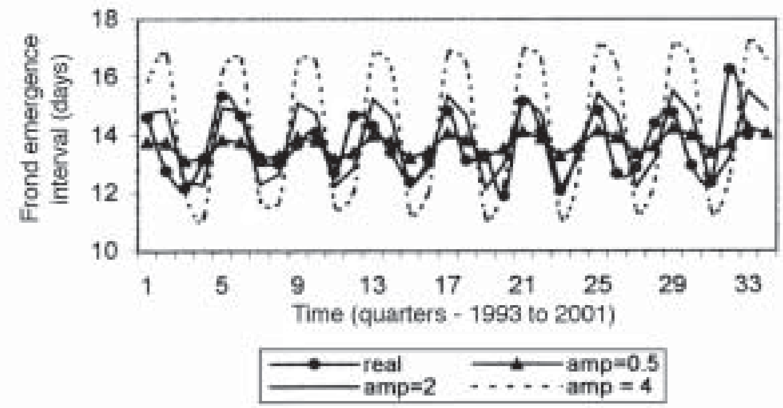
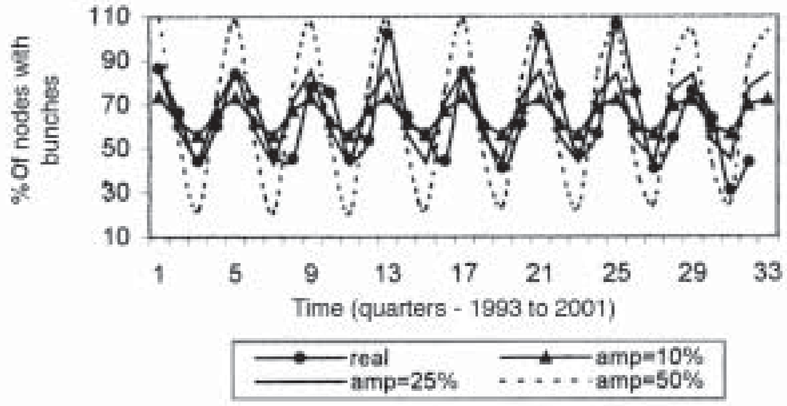
* This could not be done when examining variation in the interval between frond emergence and bunch ripening (FEBR) as these data were not recorded in the trial. Tests with this variable were initially performed without lagging.

a) Frond emergence interval lagged by -1 qtr



b) % nodes with bunches lagged by -1 qtr



c) Single bunch weight lagged by -1 qtr

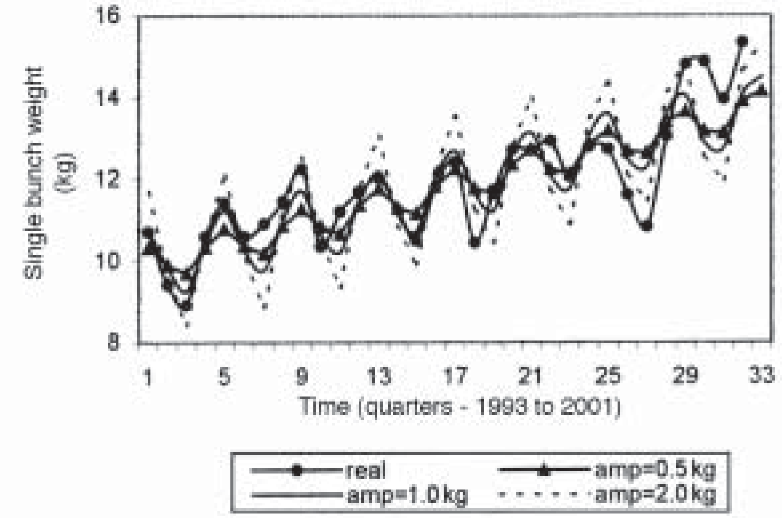


Figure 2. Comparison of observed (real) with simulated quarterly cycles of (a) frond emergence interval, (b) percentage of nodes with bunches and (c) single bunch weight, where all simulated variables are lagged by one-quarter with respect to observed variables.

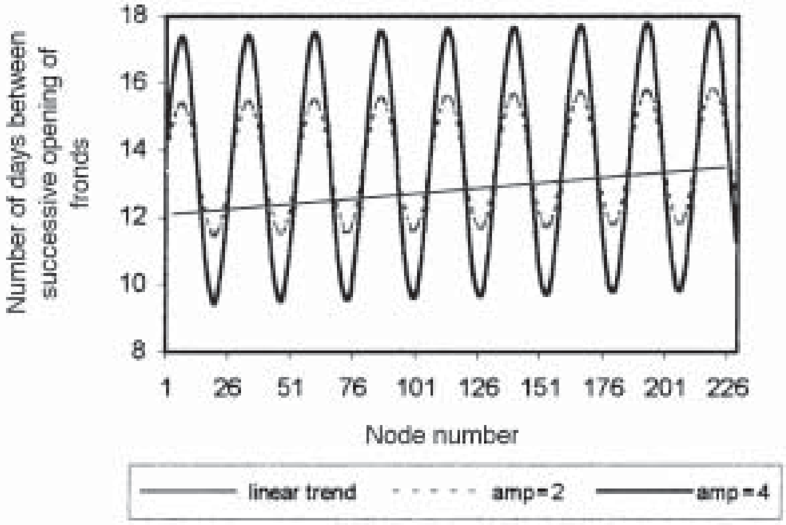


Figure 3. Examples of imposed variation in the time interval (days) between emergence of successive fronds with cumulative node number. The mean linear trend is compared with annual sinusoidal curves of different amplitudes (amp).

Based on the date of frond emergence, the date of ripening of any bunch subtended by a frond was then calculated using an appropriate value for FEBR. Unless otherwise stated, an interval of 400 days was used which could be varied within a run, again using annual sinusoidal curves differing in amplitude. Variations in the standard 400-day interval were also tested within an observed range of 350 to 500 days (Chang, pers. comm.; Chang *et al.,*1993; 1995; Lamade *et al*., 1998).

Bunch production was calculated for each node from the product of bunch number per hectare and mean weight per bunch. To facilitate comparison of simulated with observed fresh fruit bunch (FFB) yields, bunch numbers were adjusted to allow for reductions in yield due to declines in stand density. When calculating monthly bunch harvests, all bunches that ripened during a given month were taken as harvested in that month.

Bunch number per hectare was calculated from the percentage of nodes bearing female inflorescences, assuming that all females developed into ripe bunches. The resultant NWB was either taken to be constant (using the mean value) or was cyclically varied, with oscillations of different amplitudes being imposed as for frond production and inflorescence development rate.

Single bunch weight was allowed to increase with cumulative node number in accordance with the observed linear trend. Any cyclic variation used was imposed on this trend.

In order to establish the correct timing of the imposed curves, further correlations were performed using differing lag times between real and modelled monthly yields. (The latter were the results of varying each of the individual factors with the others being held constant.)

Characteristics of the factors examined are given in *Table 3.*

TABLE 3. CHARACTERISTICS OF THE FACTORS VARIED IN THE SIMULATION RUNS

Factor	Unit	Mean	Standard deviation	% CV	Cycle amplitudes tested
FEI	days	13.6	1.05	7.7	0.5, 2, 4
FEBR	days	400[1]	48.0[2]	12.0[2]	12.5, 25, 37.5
% NWB	%	64.4	18.6	28.9	10, 25, 50
SBW	kg	11.6	0.90[3]	7.8[2]	0.5, 1, 2

Notes: [1] Standard value; others also tested.

[2] Approximate only; inferred from published data of Lamade *et al.* (1998).

[3] Calculated excluding long-term trend.

RESULTS

Yields in the Absence of Cyclic Variation in Contributory Factors

In *Figure 4,* the monthly FFB yields obtained in the density trial from nine to 17 YAP (1994 to June 2002) are compared with those simulated assuming no cyclic variation in any of the underlying potentially yield-influencing components. It can be seen that even in the absence of such variation, the yields still differed from month to month, though not in a manner which matched observed changes. Apart from the linear trend due to increase in SBW, the monthly yield variation in the simulated cases was due to the variation in number of bunch ripening days falling in particular months. In both the simulated runs, there was a minimum of two harvest dates each month but sometimes three were recorded leading to there being up to three yield peaks each year. Use of a linearly decreasing, as opposed to a constant rate of frond emergence, resulted only in a small change in the distribution of such peaks.

Effects of Cyclic Variation in Frond Emergence Rate

In the field, the interval between the opening of successive fronds (as assessed quarterly from the eighth to 16 YAP) varied between 11.88 and 16.24 days, a range of 4.36 days. The effects of imposing annual cyclic variations in the rate of frond emergence on the subsequent yield cycles are shown in *Figure 5*. Best fits were obtained using a cycle amplitude of four days and with simulated yield related to real yield three months earlier (lag = +3 months; *Table 4*).

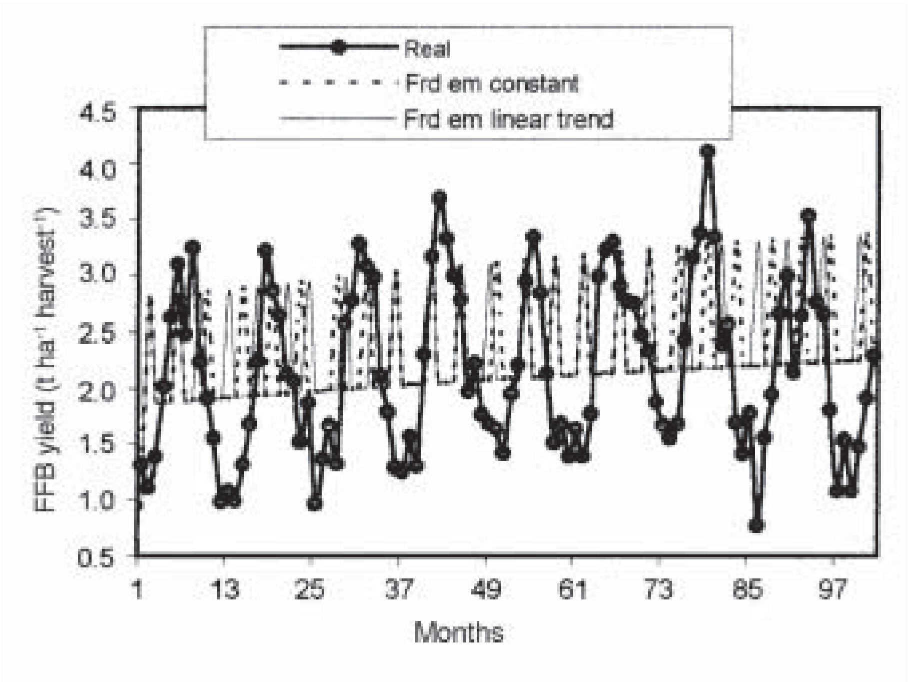


Figure 4. Monthly fresh fruit bunch (FFB) yields in a density trial (real) compared with those simulated assuming a constant rate of frond emission (Frd em constant) or a linearly decreasing rate (Frd em linear trend) and with no non-linear variation in any of the yield contributing factors. The increasing trend in yield over time is due to increases in mean bunch weight; r = 0.12 (ns).

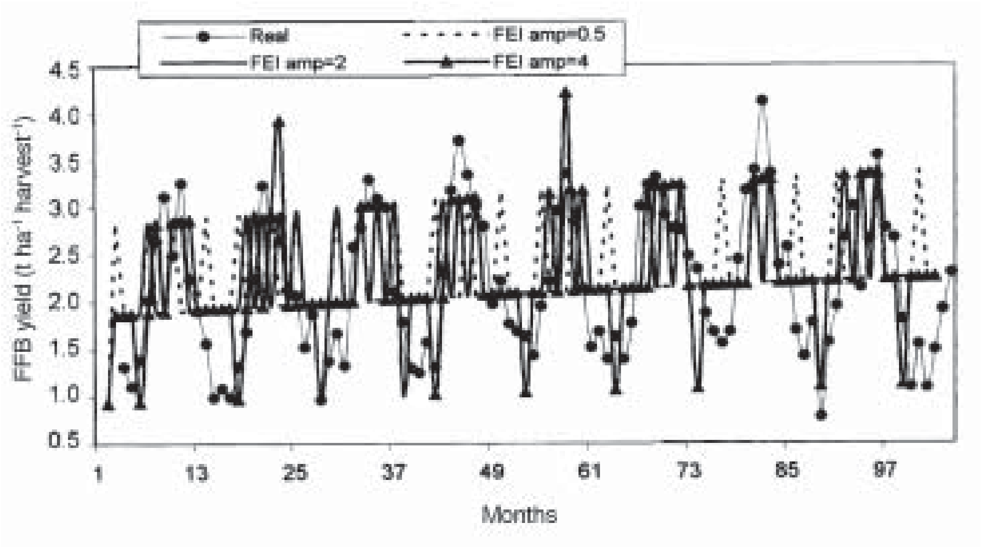


Figure 5. Monthly fresh fruit bunch (FFB) yields in a density trial (real) compared with those simulated assuming annual cyclic variation in the interval between emergence of successive fronds (FEI). Effects of three amplitudes of variation in FEI are shown. Other factors contributing to yield cycle variation were held constant. Real yields were lagged by three months with respect to simulated yields. For r values, see Table 4.

TABLE 4. THE EFFECTS OF LAGGING OBSERVED, WITH RESPECT TO SIMULATED YIELDS, ON THE COEFFICIENTS OF CORRELATION WHERE SIMULATED YIELDS ARE A CONSEQUENCE OF VARIATIONS IN AMPLITUDE OF EITHER: a) THE INTERVAL IN DAYS BETWEEN OPENING OF SUCCESSIVE FRONDS (frond emergence interval: FEI), b) THE INTERVAL BETWEEN FROND EMERGENCE AND BUNCH RIPENING (FEBR), c) THE PERCENTAGE OF NODES WITH BUNCHES (NWB) OR, d) SINGLE BUNCH FRESH WEIGHT (SBW)

Factor	Amplitude	Lag time (months)											
		5	4	3	2	1	0	-1	-2	-3	-4	-5	-6
All constant	-	0.01	0.08	0.02	0.06	0.05	0.12	0.11	0.04	0.02	0.02	0.02	-0.03
FEI (days)	0.5	0.06	0.12	**0.22**	0.19	0.14	0.10	-0.04	-0.08	-0.13	-0.13	-0.09	-0.02
	2.0	0.13	0.37	**0.47**	0.42	0.32	0.06	-0.05	-0.28	-0.41	-0.40	-0.29	-0.07
	4.0	0.37	0.58	**0.63**	0.54	0.25	-0.07	-0.27	-0.48	-0.52	-0.48	-0.37	-0.03
FEBR (days)	12.5	-0.39	-0.18	0.05	0.42	0.56	**0.58**	0.55	0.19	-0.07	-0.21	-0.45	-0.45
	25.0	-0.54	-0.32	0.13	0.47	**0.68**	0.65	0.51	0.24	-0.07	-0.31	-0.53	-0.59
	37.5	-0.55	-0.32	0.08	0.44	**0.65**	0.61	0.47	0.22	-0.05	-0.26	-0.52	-0.56
NWB (%)	10	-0.26	-0.32	-0.40	-0.28	-0.13	0.15	0.34	0.40	**0.43**	0.36	0.20	-0.03
	25	-0.43	-0.61	-0.68	-0.51	-0.25	0.13	0.47	0.63	**0.70**	0.59	0.31	-0.02
	50	-0.49	-0.72	-0.79	-0.60	-0.31	0.11	0.50	0.72	**0.79**	0.67	0.35	-0.01
SBW (kg)	0.5	-0.08	-0.04	-0.11	-0.04	-0.01	0.14	0.18	0.15	0.15	0.12	0.08	-0.03
	1.0	-0.16	-0.16	-0.23	-0.14	-0.05	0.15	0.25	0.26	**0.27**	0.22	0.13	-0.03
	2.0	-0.28	-0.36	-0.43	-0.30	-0.14	0.15	0.36	0.43	**0.46**	0.39	0.21	-0.04

Notes: Factors other than the one being tested were held constant. The most positive significant correlation in each case is indicated in bold print. Number of data pairs = 89 in all cases.

Effects of Cyclic Variation in the Time between Frond Opening and Bunch Ripening

There is considerable evidence (Corley, 1977; Chang *et al.*, 1993; 1995; Lamade *et al.*, 1998) for appreciable variation in the time between the opening or emergence of a frond and both the date of anthesis of any subtended inflorescence and the date of ripening and hence harvest, of a subsequent bunch. Simulations were run assuming the presence of annual cycles in the sum of both periods, taken to be 400 days. Three cycle amplitudes were used with other factors held constant (*Figure 6*).

It can be seen that the simulated patterns matched the real yield variations rather well when developmental time was allowed to cycle with a range of 25 days. Using an amplitude of 37.5 days led to very distinct and high peaks though these were well synchronized with real yields. Use of a 12.5-day amplitude gave split peaks. The maximum *r* value was obtained with an amplitude of 25 days and with real yields lagged one month with respect to simulated ones (*Table 4*).

Other intervals besides 400 days were also tested. As shown in *Table 5*, varying the *base* interval from 350 to 500 days had little effect on the strength of the correlation between real and simulated yields, although it did of course, change the lag time required to optimize *r*. Analysis of variance showed that there was no significant effect of the base interval.

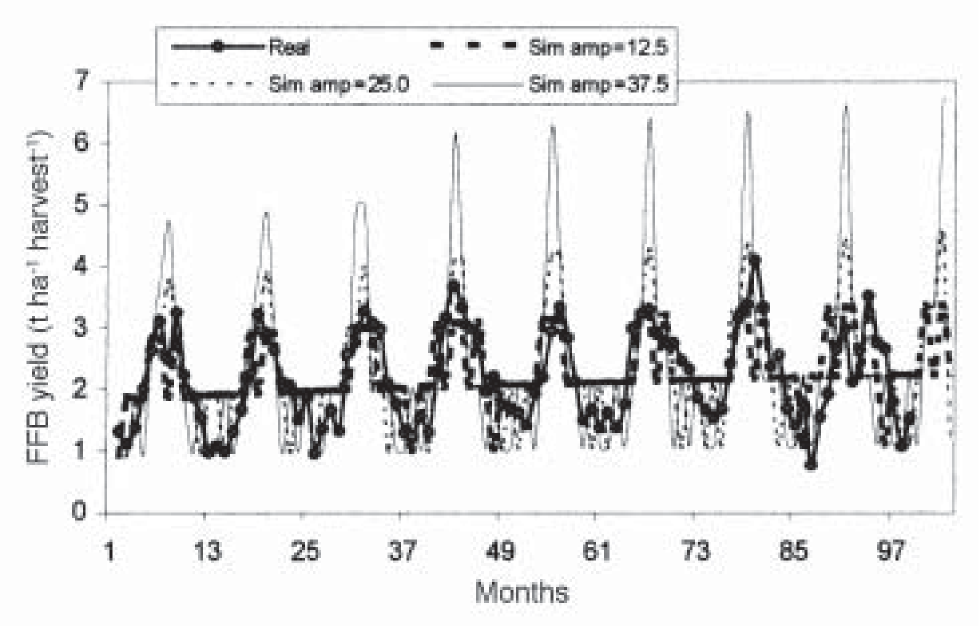


Figure 6. Monthly fresh fruit bunch (FFB) yields in a density trial (real) compared with those simulated using seasonally variable rates of inflorescence plus bunch development (measured as days from frond emergence to bunch ripening). Three cycle amplitudes were imposed. Real yields were lagged by one month with respect to simulated yields. The upward trends in yield are a result of increasing mean bunch weight. For r values, see Table 4.

TABLE 5. CORRELATION COEFFICIENTS FOR OBSERVED MONTHLY FRESH FRUIT BUNCH (FFB) YIELDS AND YIELDS SIMULATED USING DIFFERENT *BASE* INTERVALS (days) BETWEEN FROND EMERGENCE AND BUNCH RIPENING (FEBR), IN COMBINATION WITH DIFFERENT CYCLE AMPLITUDES AND WITH EITHER NO CYCLIC VARIATION IN THE PERCENTAGE OF NODES WITH BUNCHES (NWB) OR A 25% VARIATION

NWB cycle amplitude (%)	Cycle amplitude (days)	Base interval (days) from frond emergence to bunch ripening [days, with lag time (months) in brackets]			
		350 (-2)	400 (0)	450 (1)	500 (3)
0	0	0.02	0.04	0.08	-0.04
	12.5	0.59	0.64	0.61	0.56
	25.0	0.68	0.69	0.69	0.71
	37.5	0.68	0.66	0.64	0.66
	Mean	0.49	0.51	0.50	0.47
25	0	0.66	0.68	0.72	0.64
	12.5	0.77	0.79	0.79	0.78
	25.0	0.76	0.76	0.75	0.79
	37.5	0.70	0.69	0.66	0.69
	Mean	0.72	0.73	0.73	0.72

Notes: The correlations shown are those obtained using optimum lag periods between the two variables. Number of data pairs = 89.

Effects of Cyclic Variation in Bunch Numbers

The quarterly data (*Figure 1*) show regular cycling in female inflorescence numbers reflecting related variation in numbers of male and aborted inflorescences. An increase in males relative to other inflorescences was the major reason for the decline with age in bunch numbers in the trial (Henson and Tayeb, 2004; Henson and Jones, 2005). The effect of varying female, and hence numbers of bunches, was simulated with the variable, NWB. NWB was calculated from frond and bunch production per quarter, with the former lagged one and a quarter years with respect to the latter.

In the field, NWB averaged 64.4% and varied from 40.8 to over 100% (a result of imprecision using quarterly values). The effects on the subsequent yield cycles of imposing annual cyclic variation in NWB using three cycle amplitudes are shown in *Figure 7*. The maximum *r* value was obtained with an amplitude of 50 percentage points and with simulated data lagged by three months with respect to real data (*Table 4*). Some of the simulated peaks were split rather than single.

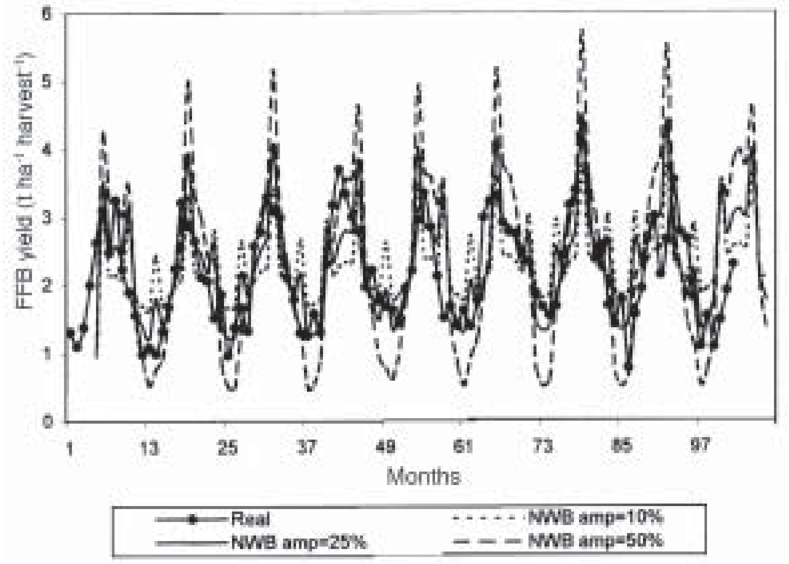


Figure 7. Monthly fresh fruit bunch (FFB) yields in a density trial (real) compared with those simulated using three seasonally variable percentages of nodes with bunches (NWB). Other yield-affecting components were held constant. To achieve maximum synchrony of peaks the simulated yields were lagged by three months with respect to the observed yields. For r values, see Table 4.

Effects of Cyclic Variation in Single Bunch Weight

It was previously observed (Henson and Tayeb, 2004) that in addition to the expected increase over time, there was also regular seasonal variation in SBW. Surprisingly, this was in phase with the cyclic change in bunch number rather than being opposed to it (as might be expected from the long-term trends in the two yield components).

The long-term increase in SBW over time was allowed for in all the simulated runs with cyclic trends being superimposed on it (*Figure 8*). From the linear regression using monthly data of SBW on node number, SBW increased from 9.74 to 13.88 kg so that the trend represented an increase of 4.14 kg. The maximum range in SBW found was 8.63 kg (7.53 to 16.16 kg) so that some 4.49 kg (*i.e.* 8.63 minus 4.14) constituted the seasonal plus random variation.

Imposing only a 0.5 kg amplitude variation in SBW did not result in any significant correlation between the simulated and observed yields (*Table 4*). However, increasing the variation to 1 or 2 kg resulted in significant correlations when simulated yield was lagged by three months (*Table 4*; *Figure 9*). However, while cycling in bunch weight could contribute to the seasonal yield pattern, it appeared to be generally much less effective than cycling in bunch number.

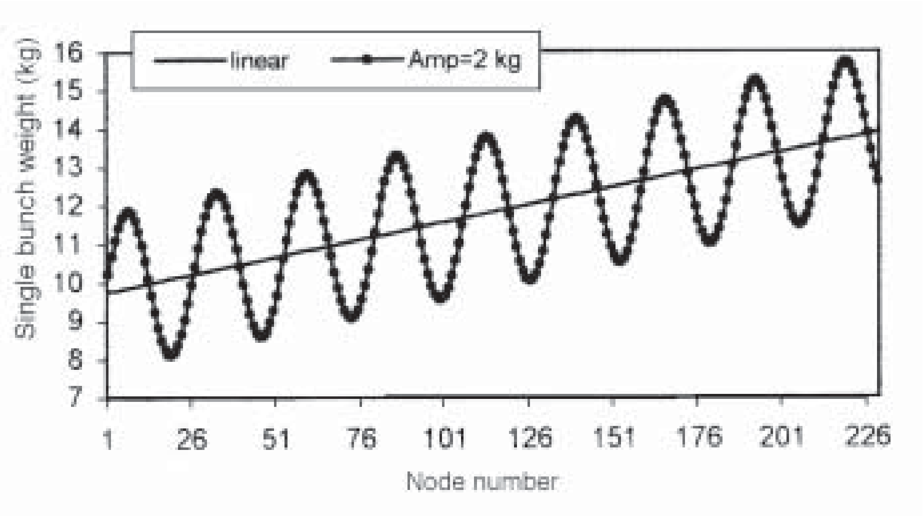


Figure 8. The linear trend in single bunch weight together with an annual sinusoidal curve used in the simulations.

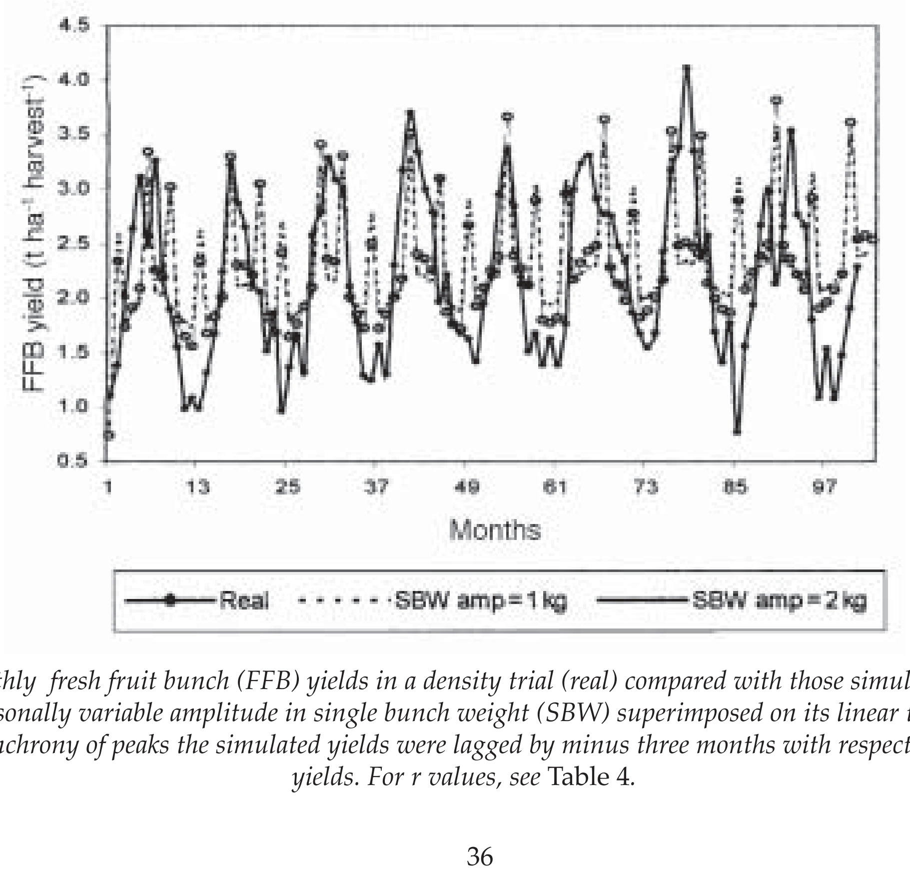


Figure 9. Monthly fresh fruit bunch (FFB) yields in a density trial (real) compared with those simulated using either a 1 or 2 kg seasonally variable amplitude in single bunch weight (SBW) superimposed on its linear trend. To achieve maximum synchrony of peaks the simulated yields were lagged by minus three months with respect to the observed yields. For r values, see Table 4.

Comparing the Effectiveness of Single Factors

The relative effectiveness of the simulations in reproducing the observed yield cycles was assessed for all factors and cycle amplitudes using simple correlations (*Table 4*). The correlations were performed with and without time lags to determine the optimum relationships. (It should be noted that the phase of the imposed oscillations was initially arbitrary so that the lack of synchrony shown in most cases between simulated and observed yields, was not unexpected.)

The highest correlation between observed and simulated yields, $r = 0.79$, was attained by varying NWB using an amplitude of 50% and a lag of minus three months, while r values of 0.68 and 0.63 were obtained by varying FEBR (amplitude = 25 days; lag = - 3 months) and FEI (amplitude = 4 days; lag = + 3 months), respectively.

Based on the foregoing correlations, the cycle phases were readjusted as necessary to achieve maximum synchrony between observed and simulated yields. The new correlations resulting from this are given in *Table 6*.

As previously mentioned, Henson and Tayeb (2004) noted that observed seasonal cycles in bunch weight were largely synchronized with those in bunch number. Hence, the yields simulated as a consequence of independently varying the two factors were often in close agreement (*e.g. Figure 10*).

TABLE 6. CORRELATION COEFFICIENTS (r) BETWEEN OBSERVED MONTHLY FRESH FRUIT BUNCH (FFB) YIELDS AND THOSE SIMULATED BY VARIATION IN AMPLITUDE OF: a) THE INTERVAL IN DAYS BETWEEN OPENING OF SUCCESSIVE FRONDS (FROND EMERGENCE INTERVAL: FEI), b) THE INTERVAL BETWEEN FROND EMERGENCE AND BUNCH RIPENING (FEBR), c) THE PERCENTAGE OF NODES WITH BUNCHES (NWB) AND d) SINGLE BUNCH FRESH WEIGHT (SBW), FOLLOWING LAGGING OF VARIABLES BASED ON INITIAL COMPARISONS

Factor	Amplitude	r	P
All constant	none	0.004	ns
FEI (days)	0.5	0.126	ns
	2.0	0.457	0.001
	4.0	0.703	0.001
FEBR (days)	12.5	0.532	0.001
	25.0	0.680	0.001
	37.5	0.658	0.001
NWB (%)	10	0.404	0.001
	25	0.669	0.001
	50	0.772	0.001
SBW (kg)	0.5	0.125	ns
	1.0	0.244	0.05
	2.0	0.435	0.001

Notes: Factors other than the one being tested were held constant. Number of data pairs = 89. ns = not significant.

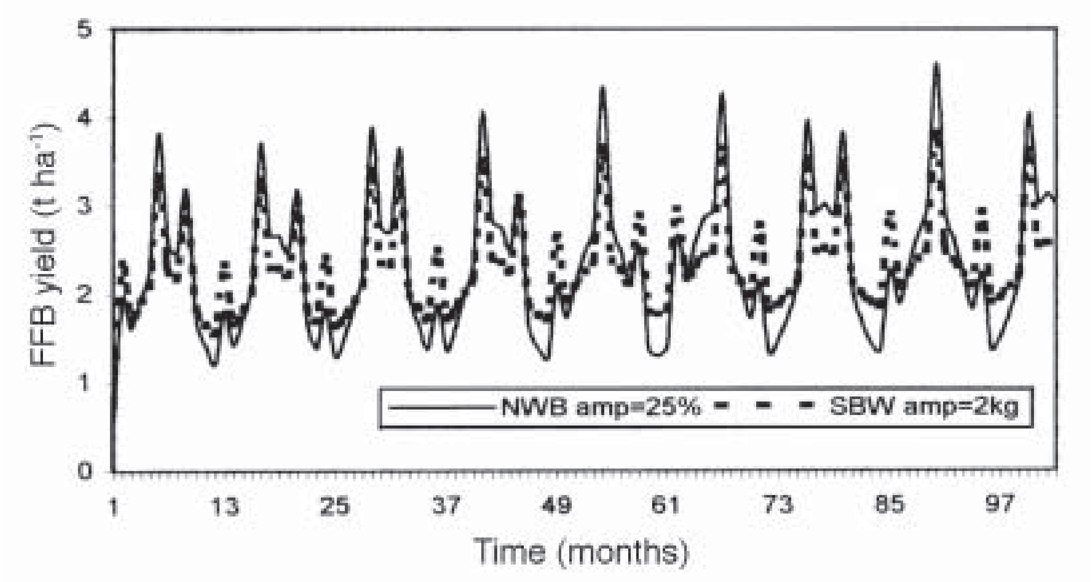


Figure 10. A comparison of simulated yields obtained by imposing seasonal cycling in bunch numbers (NWB) or in single bunch weight (SBW). All other factors were maintained constant.

Effects of Combining Factors

Using the readjusted cycle phases, the effect of combining factors on the correlation between observed and simulated yields was tested to determine whether further improvements in r values were possible. The following combinations were assessed:

i) FEI + FEBR
ii) FEI + NWB
iii) FEBR + NWB
iv) FEI + FEBR + NWB
v) NWB + SBW
vi) FEI + FEBR + NWB + SBW

Figure 11 shows the effects on the correlation coefficient of combining FEI with FEBR, FEI with NWB and NWB with SBW. Variation in FEBR had its greatest effect in the absence of, or at low levels of, variation in FEI. For FEBR, the intermediate level of variation gave better correspondence with real yields than the higher level, especially with strong FEI cycling. The same was true for the factor NWB when combined with FEBR. The relatively weak effect of SBW variation is evident in the lower panel of *Figure 11.*

In general, combining the factors failed to increase r values beyond those obtained using the highest cycle amplitudes of the single factors.

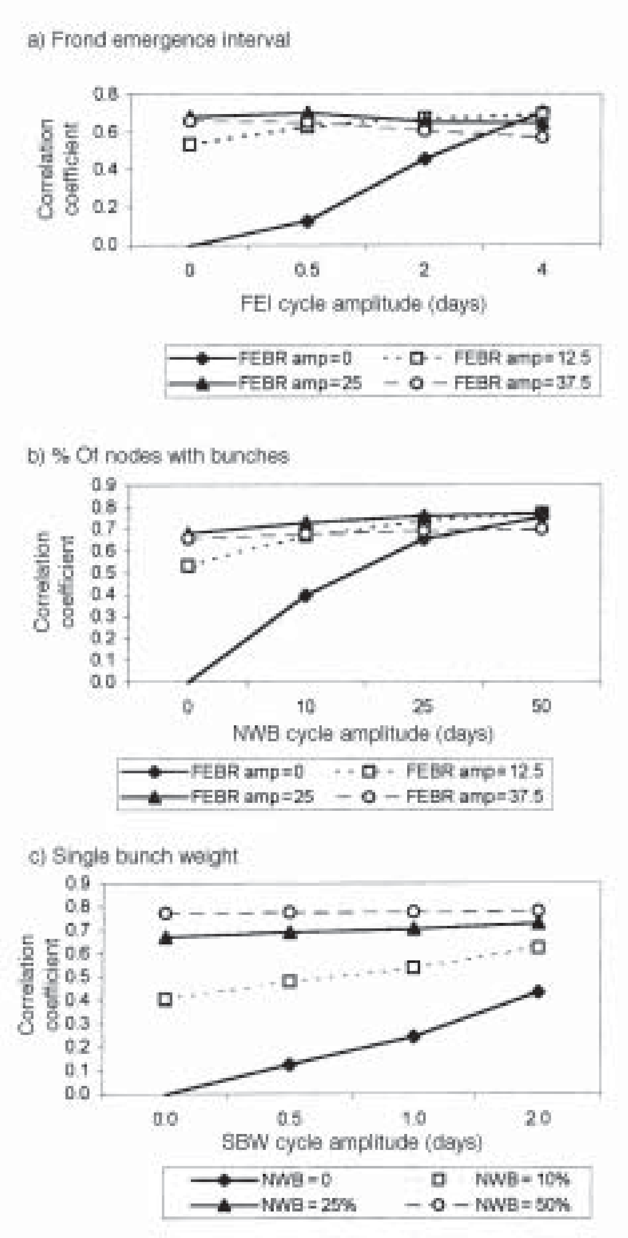


Figure 11. Effects of combining components influencing bunch yield on the correlation between observed and simulated yields. In (a), four frond emergence interval (FEI) cycle amplitudes are combined with four frond emergence to bunch ripening (FEBR) amplitudes, while in (b), four nodes with bunches (NWB) cycle amplitudes are combined with four FEBR amplitudes. In (c), four single bunch weight (SBW) cycle amplitudes are combined with four NWB amplitudes.

Further results from combining the factors are presented in *Figure 12*. Again, there was a limit to the improvement in correlation achieved by factor combination. Interactions were evident between the level of FEI variation and that of FEBR.

Introduction of Randomness in the Simulations

Attempts to introduce a random element into either the phase or amplitude of simulated cycles were unsuccessful. Generally, randomness increased with time instead of being evenly distributed during the simulation. Further efforts are required to examine this aspect.

DISCUSSION

Interest in yield cycles and their causes arises from both practical and theoretical considerations. Although oil palm is a continuously producing crop (except under extreme conditions), the unevenness of the production with annual peaks and troughs, while much less than that for many other crops, is still a cause for concern. Dissecting the processes underlying the yield pattern represents the first step towards an understanding of the problem. Simulation modelling can play a role in this as it facilitates both the analysis of existing data and enables potential effects of new scenarios to be readily investigated.

It is self evident that the cycling of yield is a consequence of the cycling in underlying yield-forming or contributing processes. This simulation exercise, which examined some of these processes either directly or indirectly, indicated that given sufficient variation, any one of them (with the possible exception of SBW) could account for a large proportion of the yield variation. The effect of an individual factor depends, not unexpectedly, upon the degree of variation that it exhibits, so it is necessary to use cycle amplitudes which are not excessive and which occur in the field. In this respect, from *Figure 2*, the most suitable amplitudes were, for FEI, two days; NWB, 25% and SBW, 1 kg. For FEBR, direct data from the trial were lacking but the simulation results (*Figures 6, 11* and *12* and *Tables 4* and *6*) suggested that 25 days rather than the more extreme 37.5 days was an appropriate value, even though much greater variation has been observed

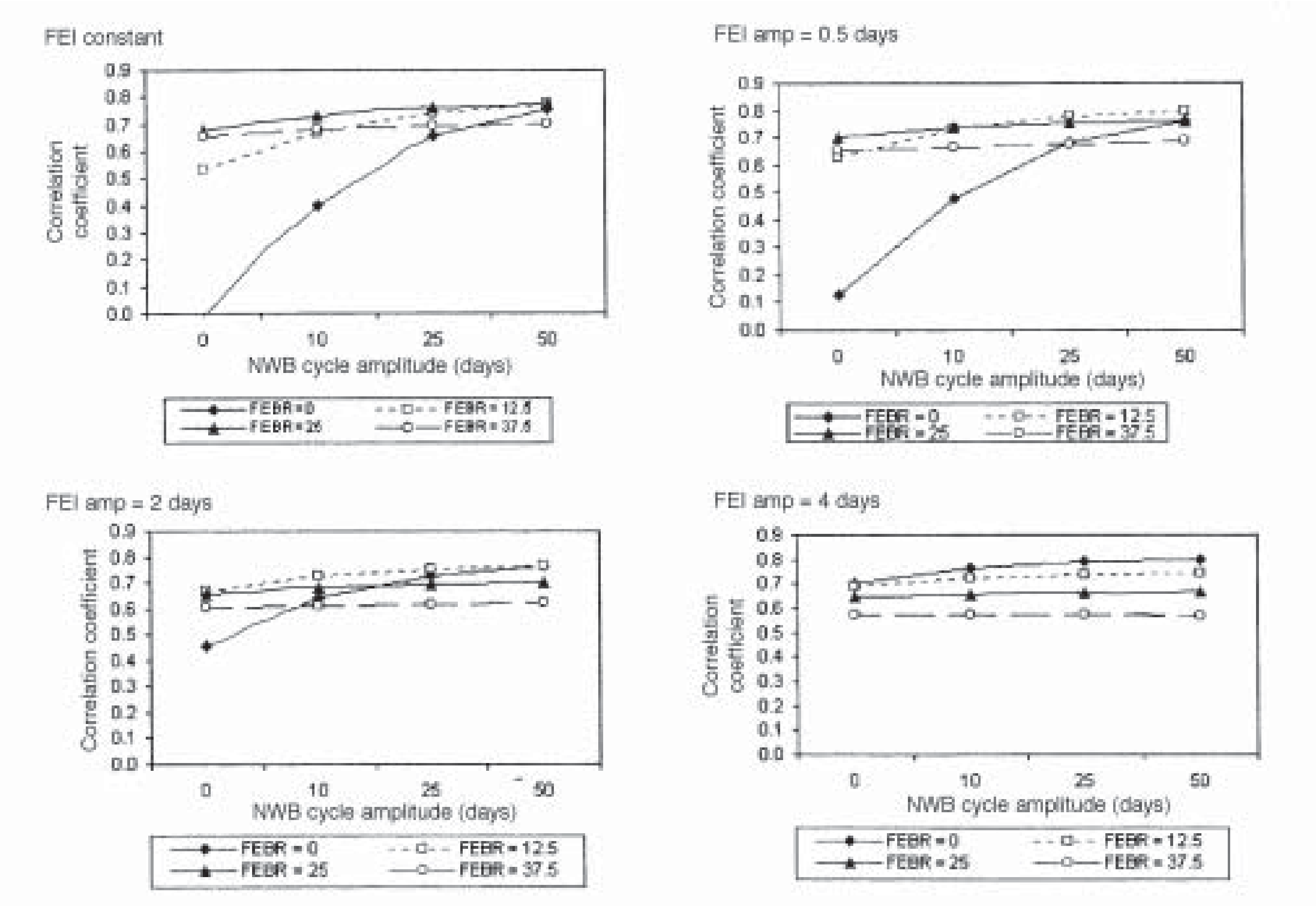


Figure 12. Effect on the correlation coefficient between observed yields and simulated yields of different levels of cyclic variation in nodes with bunches (NWB), frond emergence to bunch ripening (FEBR) and frond emergence interval (FEI). The same combinations of FEBR and NWB are shown in all four panels which differ only according to the FEI cycle used.

in individual palms (Chang *et al*., 1995; Lamade *et al*., 1998).

The need to lag the simulated cycles to optimize the correspondence between observed and simulated yields was not unexpected as there was no *a priori* reason for synchronizing the phase of all cycles to the start of the simulation. As cycles in both NWB and SBW were known to be synchronized in the palm the need to lag both by the same extent; *i.e.* minus three months, was also in line with expectations. As mentioned, prior knowledge of the timing of the FEBR cycle was lacking but best fits were obtained with a lag of either one month or none. This implies that the maximum rate of development (*i.e.* the shortest interval) occurred for fronds emerging in September while the slowest rate was for fronds emerging in March. An amplitude of 25 days implies a range of 50 days or nearly two months in the time of bunch ripening and largely accounts for the variation in the frond numbers (positions) corresponding to anthesis and harvest (Henson and Tayeb, 2004). Because the inflorescence plus bunch development takes well in excess of a year it is not possible to relate its speed to seasonal conditions. Only the total time from frond emergence to bunch ripening was considered here although it is known that there is variation in both the time to anthesis and the time taken from anthesis to bunch ripening. The extent to which the duration of the two periods is correlated needs to be determined before a more detailed analysis is undertaken.

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