

MODELING PIGEONPEA PHENOLOGY

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RAO, S. C., SAXENA, K. B., PACHEPSKY, L. B. and REDDY, V. R. *Modeling Pigeonpea Phenology*. International Journal of Biotronics **31**, 85-100, 2002. Pigeon pea [*Cajanus cajan* (L.) Millsp.] is widely grown in tropical and sub-tropical areas. However, we are not aware of any pigeonpea simulation model that can assist farmer decision-making. A phenological module is one of the major elements of the crop model because an accurate prediction of the timing of growth stages is essential for correct modeling of physiological responses under variable field conditions. Phenological observations were conducted during 7 years on 14 early maturing genotypes at three different locations, ICRISAT (17°32'N; 78°16'E), Hissar (29°10'N; 75°46'E), India, and El Reno (35°40'N; 98°00'W), Oklahoma, USA. Models of rates of vegetative and reproductive development of pigeonpea, as dependences of phenological characteristics on temperature and photoperiod were developed, parameterized for these three locations and tested with the published controlled environment experimental data. The dependencies of rates of development on temperature were linear and contained two parameters. The relationships of rates of both vegetative and reproductive rates of development with photoperiod were nonlinear with five parameters, one of which was a function of location. All of these parameters can be determined by a routine optimizing procedure for any other location. The analysis showed that interactions between two major factors of pigeonpea development, temperature and photoperiod are essential and are to be accounted for in the model.

Key words : Pigeon pea ; *Cajanus cajan* ; Phenology ; Modeling.

INTRODUCTION

Pigeon pea is a crop of vital importance in tropical countries, especially in India, Nigeria, and Ghana where it is used not only as a major source of protein in human diets but also as forage for livestock (8). It is also cultivated in Australia, USA, Indonesia, and some countries of South America because of its nutritional qualities and drought tolerance (4).

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Pigeonpea phenology is strongly affected by temperature (5, 6, 13) and photoperiod (11). Omanga *et al.* (11) noted that field observations of flowering in pigeonpea were usually interpreted mostly in terms of reactions to photoperiod (15, 16). The vegetative stage becomes longer when photoperiod exceeds a genotype-specific value (2, 7, 17). Omanga *et al.* (11) emphasized that the effect of temperature on the rates of pigeonpea development can be similar in magnitude to those of photoperiod. Phenological studies in the controlled environments conducted by Ellis *et al.* (4), Summerfield and Roberts (19), and by McPherson *et al.* (9) have confirmed it. Turnbull *et al.* (19) in the controlled environment studies showed that warm ($>28^{\circ}\text{C}$) and cool ($<20^{\circ}\text{C}$) temperature delay flower initiation and that the optimal temperature for flowering early maturing types is close to 24°C .

Pigeonpea has been studied less than other legumes. A growth simulation model for pigeonpea as a module of APSIM model (10), has been recently published by Robertson *et al.* (14). It has not been described in detail, especially its phenological component. Phenological module is an essential part of any crop model and a reliable basis for modeling physiological responses under variable field conditions. The data of field phenological observations for fourteen early maturing genotypes collected in three distinctly different locations, ICRISAT ($17^{\circ}32'\text{N}$; $78^{\circ}16'\text{E}$), Hissar ($29^{\circ}10'\text{N}$; $75^{\circ}46'\text{E}$), India, and El Reno ($35^{\circ}40'\text{N}$; $98^{\circ}00'\text{W}$), Oklahoma, USA allowed us to model the phenology of pigeonpea.

The objectives of this study were (1) to analyze the dependencies of pigeonpea phenological characteristics on the major environmental factors, (a) temperature, (b) photoperiod, and (c) precipitation, (2) to develop a model of pigeonpea phenology for both vegetative and reproductive stages of development, and (3) develop an algorithm of parameterization of this model for any particular location.

MATERIALS AND METHODS

Phenological observations were conducted from 1988 to 1994 in three distinctly different latitude locations, in the fields of ICRISAT, India ($17^{\circ}32'\text{N}$; $78^{\circ}16'\text{E}$) Hissar, India ($29^{\circ}10'\text{N}$; $75^{\circ}46'\text{E}$, elevation 215 m), and Grazinglands Research Laboratory, USDA-ARS, El Reno, Oklahoma, USA ($35^{\circ}40'\text{N}$; $98^{\circ}0'\text{W}$, elevation 414 m). Meteorological observations were made by standard meteorological stations located at the experimental field or less than 100 m from the sites of observations.

The field experimental scheme is shown in Table 1. Fourteen pigeonpea genotypes were studied in ICRISAT and Hissar, India, and the cultivar ICPL-87 was observed for three years in El Reno, Oklahoma, United States. No irrigation was provided for the crops in all three sites. In ICRISAT and Hissar the experimental plots were placed on Alfisols (Udic Rhodustalf) soil, and in El Reno the experimental fields were located on sandy loam Mollisols soil. Planting dates were different for different locations (Table 1) because of differences in climate conditions. All genotypes were planted between 18 and 21 of June in ICRISAT. In Hissar, there were 10 days differences in planting dates between 1988 and 1989, because of a drought in June 1989. All three dates of planting were different in El Reno (Table 1), because the weather conditions were much more variable from year to year in Oklahoma than in

Table 1. Scheme of field experiment conducted in three locations with various pigeonpea genotypes. Planting dates are shown in a numerator, yield, kg ha⁻¹, is given in a denominator.

Genotypes	ICRISAT, India, 17°32'N					Hissar, India, 29°10'N		El Reno, OK, 35°40'N		
	1988	1989	1991	1992	1993	1988	1989	1992	1993	1994
ICPL-4	<u>June21</u> 865	<u>June19</u> 3114	<u>June19</u> 1301	<u>June18</u> 1133	<u>June20</u> 1580	<u>June28</u> 3295	<u>July07</u> 2440	—	—	—
ICPL-87	<u>June21</u> 2563	<u>June19</u> 3145	<u>June19</u> 1301	<u>June18</u> 1151	<u>June28</u> 1140	<u>June28</u> 1905	<u>July07</u> 2515	June21	June16	May31
ICPL-151	<u>June21</u> 2767	<u>June19</u> 2724	<u>June19</u> 3120	<u>June19</u> 1787	<u>June20</u> 1151	<u>June28</u> 1849	<u>July07</u> 2913	—	—	—
UPAS-120	<u>June22</u> 2260	<u>June19</u> 3122	<u>June19</u> 2242	<u>June19</u> 1122	<u>June20</u> 2220	<u>July02</u> 2029	<u>July07</u> 2948	—	—	—
MANAK	<u>June22</u> 1625	<u>June19</u> 2010	—	<u>June18</u> 1306	<u>June20</u> 1812	<u>July02</u> 1997	<u>July07</u> 1802	—	—	—
83105	<u>June21</u> 2346	<u>June19</u> 2425	—	—	—	<u>June28</u> 1059	<u>July07</u> 3030	—	—	—
83006	<u>June21</u> 2772	<u>June19</u> 2694	—	—	—	<u>June28</u> 1840	<u>July09</u> 3153	—	—	—
83109	<u>June21</u> 1464	—	—	—	—	<u>June28</u> 1603	—	—	—	—
84023	<u>June21</u> 1958	<u>June19</u> 1950	—	—	—	<u>June28</u> 1418	<u>July26</u> 2449	—	—	—
85010	<u>June21</u> 2290	<u>June19</u> 2087	—	—	—	<u>June28</u> 1366	<u>July09</u> 3102	—	—	—
88009	—	—	<u>June19</u> 1181	<u>June18</u> 1536	<u>June20</u> 1960	—	—	—	—	—
90008	—	—	<u>June19</u> 1184	<u>June18</u> 1340	<u>June20</u> 2030	—	—	—	—	—
90012	—	—	<u>June19</u> 1023	<u>June18</u> 1639	<u>June20</u> 1900	—	—	—	—	—
90011	—	—	<u>June19</u> 1165	<u>June18</u> 1387	<u>June20</u> 1340	—	—	—	—	—

both locations in India.

Phenological observations were conducted according to the same protocol in all three locations during all years of observation. After 50% flowering (when 50% of the plants had at least one flower) plants were inspected on alternate days. In both ICRISAT and Hissar the observations were conducted on three plots of 2.16

m². Plants were planted in rows 4 m long with 60 cm distance between rows. In El Reno the observations were made on plots of 18 m², where row length was 6 m and row spacing was 60 cm, in three replicates as well. An average plant population varied from 60,000 to 80,000 plants/ha.

Phenological characteristics, duration of the vegetative, D_{veg} , and reproductive, D_{gen} , stages and of the whole period of growth, D_{whole} , all in days, as well as heat units for the same periods, H_{veg} , H_{gen} , and H_{whole} were observed and calculated. To predict plant growth duration as well as the duration of the particular phenological stages as functions of temperature, heat units (thermal time), H , dd (degree-days), are usually used:

$$H = \sum_1^n (T_a - T_b) \quad [1]$$

where T_a is daily mean air temperature, T_b is the base temperature, n is the number of days of observation (13). The base temperature was estimated in (1) as equal to 13°C.

ANOVA analysis was used to determine the factors affecting the durations and the heat units of vegetative and reproductive stages. To roughly estimate the effect of water availability on pigeonpea development, relations of the phenological characteristics to the sum of precipitation were studied using regression and correlation analysis.

Models' equations were developed on the basis of this preliminary statistical analysis. Linear, exponential, hyperbolic, logistic, and polynomial equations were tested, and the best ones, statistically justified, have been chosen. A modified Marquardt algorithm was used to obtain parameter values that minimized the lack-of-fit mean square and to estimate standard errors of the parameters. An unbiased estimator of the model's standard error, s_r (12) is the following:

$$s_r^2 = \frac{\sum_{i=1}^N m_i [R_{i,calc} - \overline{R_{i,obs}}]^2}{N - K} \quad [2]$$

where $R_{i,obs}$ is the average value of R found the i th observation, $R_{i,calc}$ is the average value of R estimated for the i th observation from equations of the model depending on which equation is being fitted to the data; N is the total number of observed average values of R ; m_i is the number of replications of the observations at the i th average value of R ; and K is the number of parameters in the equation being fitted. We used a version of the algorithm published by Van Genuchten (21). Having the standard errors of the parameters available allowed testing for significant differences between parameter values.

To assess the adequacy of the models, we employed criteria based on a statistical comparison of the lack-of-fit mean square s^2 and the pure error s_e^2 (12). The latter is estimated as

$$s_e^2 = \frac{1}{M - N} \sum_{i=1}^N \sum_{j=1}^{m_i} (R_{ij,obs} - \overline{R_{i,obs}})^2 \quad [3]$$

where M is the total number of observations and $R_{ij,obs}$ is the j th observation made to obtain the i th average value of R . The hypothesis that s^2 is equal to s_e^2 is then

tested. The value of the F -ratio given by the equation

$$F = s_r^2 / s_e^2 \quad [4]$$

is then compared with the value of $F_{N-K, M-N}$ (i.e., the F -distribution value at a given level of significance). If $F < F_{N-K, M-N}$, the hypothesis that the model is adequate can be accepted.

RESULTS AND DISCUSSION

A significant difference in photoperiod dynamics between the three locations (Fig. 1) allowed us to study the effect of this factor on phenological characteristics. The longest days among the three sites were in El Reno during the vegetative and the early part of the reproductive stages of pigeon pea development. After the equinox, the day length was shorter than that in ICRISAT and Hissar. At solstice, a photoperiod in El Reno was almost 1.5 hours greater than in ICRISAT and about 0.6 hours longer than in Hissar (Fig. 1).

Weather conditions were significantly different for the three locations (Table 2). In ICRISAT, the air temperature demonstrated a quite stable pattern during all five years of observations. Maximum temperature during the whole growing season was in a range from 25 to 35°C with few exceptions, with a mean close to 30°C. Minimum temperature varied in a range from 20 to 25°C, with a mean close to 23°C. Minimum temperature fell under 20°C after October 7 when the growing season

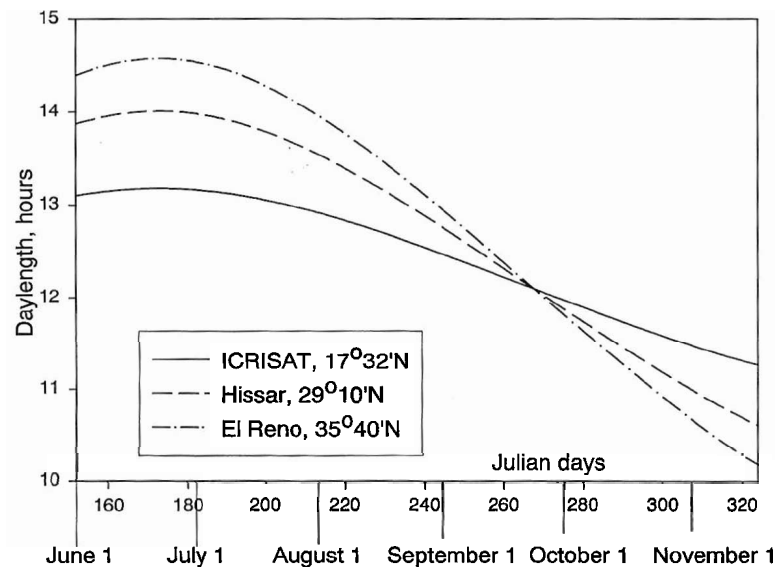


Fig. 1. Changes in daylength in three experimental locations during a pigeon-pea growing season calculated for the corresponding latitude.

Table 2. Air temperature (maximum, T_{max} , minimum, T_{min} , and mean daily, T_{mean} , values), °C, and sums of precipitation, Σ , mm, for periods of pigeonpea growth at three locations of field experiments.

Years	T_{max}	T_{min}	T_{mean}	Σ
ICRISAT				
1988	40.7	12.0	25.8	816.1
1989	36.0	12.5	25.6	909.2
1991	34.0	22.1	26.3	552.4
1992	39.0	13.0	21.5	534.4
1993	36.5	19.5	26.5	538.4
Hissar				
1988	45.7	13.5	29.4	613.3
1989	42.1	7.0	28.0	101.0
El Reno				
1992	36.1	6.7	24.4	284.2
1993	38.9	6.1	26.9	366.5
1994	41.1	5.6	26.2	201.0

was already over. Precipitation in ICRISAT occurred regularly during all five years of observations. The sum of precipitation in 1988 and 1989 were about 1.6 fold higher than that in 1992–1994 (Table 2). In Hissar the temperature regime was quite similar in 1988 and 1989. The maximum temperature was higher than in ICRISAT varying between 30 and 40°C. The minimum temperature ranged from 23 to 30°C during the vegetative stage. It was over 20°C during the first half of the reproductive stage and then fell down to 15°C in 1988 and to 12°C in 1989. There was a remarkable difference in the amount of precipitation between 1988 (613 mm) and 1989 (101 mm) (Table 2). In El Reno meteorological observations were carried out only during the vegetative stage. Both maximal and minimal temperatures varied in much wider ranges than in both ICRISAT and Hissar. The pattern of the temperature regime was different in 1992, 1993 and 1994. Precipitation in El Reno ranged from 200 mm in 1994 to 366 mm in 1993 (Table 2).

Mean and extreme values of the measured and calculated phenological characteristics are shown in Table 3. ANOVA analysis showed that a location was a significant factor for all characteristics except the duration, D_{gen} , and the heat unit, H_{gen} , of reproductive stages for some genotypes. There was a significant difference in duration and heat unit of vegetative stages, D_{veg} and H_{veg} , between cultivars ICPL-4, ICPI-87 and MANAK, and no significant difference between other cultivars. For both D_{gen} and H_{gen} , there was no significant differences between cultivars.

For all cultivars and lines, the duration of the vegetative period was longer in Hissar than in ICRISAT (Table 3). The longest was the duration of the vegetative stage

Table 3. Maximum, minimum, and mean values of phenological characteristics (described in the text) of pigeonpea genotypes at various locations.

	D_{veg} , days	H_{veg} , degree-days	D_{gen} , days	H_{gen} , degree-days	D_{whole} , days	H_{whole} , degree-days
<u>ICRISAT</u>						
Maximum	71.9	963	48.5	687	116	1563
Minimum	53	699.2	37.4	486	96	1253.9
Mean	65.6	863	43.3	557.9	104.35	1966.3
<i>Hissar</i>						
Maximum	76.5	1352.4	54.5	682.2	130.5	1964.2
Minimum	54	944.1	29.5	429.3	101	1626.3
Mean	70.4	1238.4	44.8	593.8	115.1	1841.9
<i>El Reno</i>						
Maximum	101.9	1479.4	—	—	—	—
Minimum	85.5	1085.4	—	—	—	—
Mean	93.7	1282.4	—	—	—	—

of ICPL-87 in El Reno, 94 days, exceeding that of the same genotype in ICRISAT by 23% and in Hissar by 18%. The total heat units for the vegetative stage for all compared genotypes were about 30% greater for Hissar than for ICRISAT. Unlike the duration of the vegetative stage, the sum of heat units in El Reno was 25% higher than in ICRISAT but 3% lower than in Hissar (Table 3).

To estimate the effect of water availability on pigeonpea development, relations of the phenological characteristics with the sum of precipitation were studied. Table 4 presents the results of the regression and correlation analysis. The results were quite different for the vegetative and reproductive stages. Both the duration, D_{veg} , and the heat unit, H_{veg} , of the vegetative stage were in a significant and strong correlation with the sum of precipitation during the corresponding period. All slopes of the regression equations were of the same order of magnitude, except for Hissar-89, where the amount and sum of the precipitation were very low as compared with all other treatments. For the reproductive stage, there were only two significantly different from zero coefficients of correlation, both D_{gen} and H_{gen} correlated with the sum of precipitation Σ in ICRISAT in 1991, $r^2=0.81$, and 0.69, respectively. Therefore, precipitation affected mostly the vegetative stage of the pigeonpea development.

Fig. 2 presents the dependencies of rates of vegetative development on temperature and photoperiod. The latter affected the rates of development significantly; a relation between rates of development and temperature was weak because the influence of photoperiod obscured these dependences. Therefore, the model should account for both factors simultaneously, in their interactions. Besides, the effect of location (precipitation) had to be accounted for in the model.

Table 4. Coefficients a and b of the linear regressions $Y=aX+b$ where Y stands for pigeonpea durations of vegetative and reproductive stages, D_{veg} and D_{gen} , days, and heat units H_{veg} and H_{gen} , degree-days, and X is the sum of precipitation, Σ , mm, during the corresponding periods; r^2 is a coefficient of determination, values with asterisk are significantly different from zero.

Locations and years	D_{veg}			H_{veg}			D_{gen}			H_{gen}		
	a	b	r^2	a	b	r^2	a	b	r^2	a	b	r^2
ICRISAT-88	0.08	25.27	0.89*	1.01	375.2	0.89*	-0.04	64.6	0.31*	-0.36	767.2	0.21
ICRISAT-89	0.22	-56.68	0.97*	3.0	-841.44	0.98*	-0.02	48.8	0.01	-0.08	588.11	0.01
ICRISAT-91	0.39	-91.47	0.88*	4.7	-1023.4	0.85*	0.07	29.31	0.81*	0.93	424.0	0.69*
ICRISAT-92	0.45	-143.6	0.89*	5.5	-1621.3	0.9*	0.21	22.91	0.19	2.37	324.25	0.15
ICRISAT-93	0.14	15.7	0.77*	1.44	409.1	0.63*	0.04	35.06	0.03	1.76	208.84	0.55
Hissar-88	0.25	-7.28	0.76*	3.99	6.99	0.64	0.05	29.86	0.05	1.5	147.93	0.39
Hissar-89	1.51	-75.88	0.93*	27.5	-1402	0.93*	0.3	45.5	0.01	20.5	539.43	0.21*

The following model has been suggested:

$$R_{veg} = (B_1 + B_2 \times PhP) \times (T - t_b) \quad [5]$$

$i=1$ for ICRISAT, $i=2$ for Hissar, $i=3$ for El Reno,

where R_{veg} is the rate of vegetative development, 1/d, PhP is photoperiod, hours, T is air temperature, °C, t_b is the base temperature equal to 13°C, B_1 - B_3 are the parameters determined with our experimental data. Values B_1 , B_2 , and B_3 were determined with the data for ICRISAT, Hissar, and El Reno, respectively, i refers to the particular location. Table 5 shows the values of these parameters.

Equation [5] expresses the linear dependencies of rates of vegetative development on photoperiod and temperature in a nonlinear interaction (two linear functions multiplied). Fig. 3 shows a good correspondence between calculated and measured rates of vegetative development for all three locations, $r^{2*}=0.99$.

Fig. 4 presents the dependences of rates of reproductive development on temperature (a) and photoperiod (b) for ICRISAT and Hissar. The correlation between rates of reproductive development and temperature, $r^{2*}=0.34$, is significantly different from zero. The data for the group of cultivars in ICRISAT (closed circles) and for the group of lines seem to belong in the same set on the temperature plot and to slightly different sets on the plots for photoperiod. The dependence for ICRISAT on photoperiod appears to be much stronger than the dependence on temperature, $r^{2*}=0.68$. Nevertheless, both dependences seem to be complicated by the interactions between two factors, temperature and photoperiod. Fig. 5 shows that the dependence of the rate of reproductive development on photoperiod is non-linear. The best result was obtained by fitting the data to the polynomial function:

$$R_{gen} = -25.0 + 6.49 * PhP - 5.23 * PhP^2 + 0.016 * PhP^3 \quad [6]$$

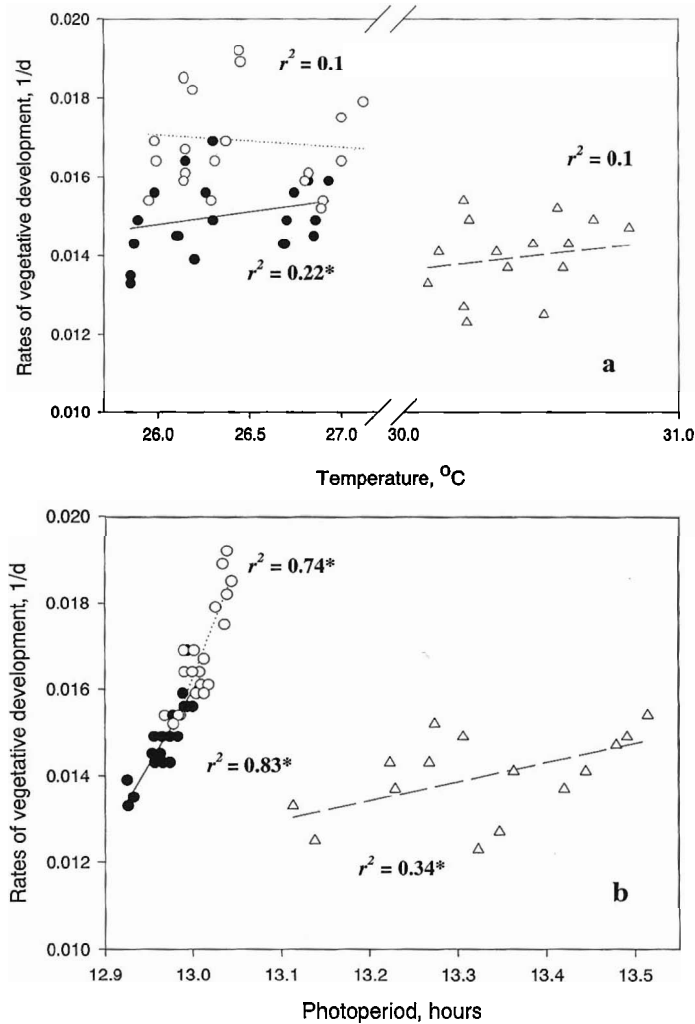


Fig. 2. Effect of temperature (a) and photoperiod (b) on rates of pigeonpea vegetative development for group of cultivars (closed circles, solid line) and group of lines (open circles, dotted line) in ICRISAT, and crops in Hissar (triangles and dashed line), corresponding values of the coefficient of determination values are marked with an asterisk if the value differs significantly from zero. Groups of cultivars and lines are defined in Table 1.

Currently, there is not enough knowledge to propose a physiologically meaningful function to simulate the effect of photoperiod on the rates of plant development. Photoperiodism is controlled by phytochrome, related to the circadian rhythm, and interacts with a hormonal regulation system in the plant. These mechanisms, each studied rather qualitatively and for the species most convenient for experimental

Table 5. Parameters of the model of pigeonpea phenology, equations [5] and [7].

Parameters	Mean values	Standard errors
<i>Vegetative stage</i>		
B_1 (ICRISAT)	-0.0052	0.0016
B_2 (Hissar)	-0.0057	0.0017
B_3 (El Reno)	-0.0059	0.0017
B_4	0.00049	0.00012
<i>Reproductive stage</i>		
G_1 (ICRISAT)	-40.75	$0.3 \cdot 10^{-12}$
G_2 (Hissar)	-39.2	$0.3 \cdot 10^{-12}$
G_3	24.3	$0.3 \cdot 10^{-12}$
G_4	-3.65	6.3
G_5	0.1	0.53
G_6	-0.0000175	0.0003

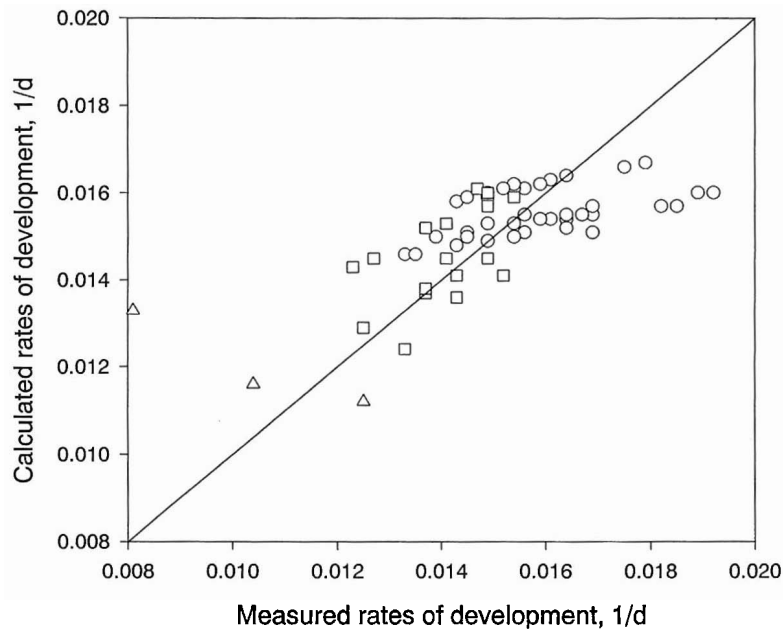


Fig. 3. 1:1 diagram for measured and calculated with the model [5] values of the pigeonpea development rates for the vegetative stage. Circles represent the crops in ICRISAT, squares correspond to the crops in Hissar, and triangles mark the crops grown in El Reno, $r^{2*}=0.99$.

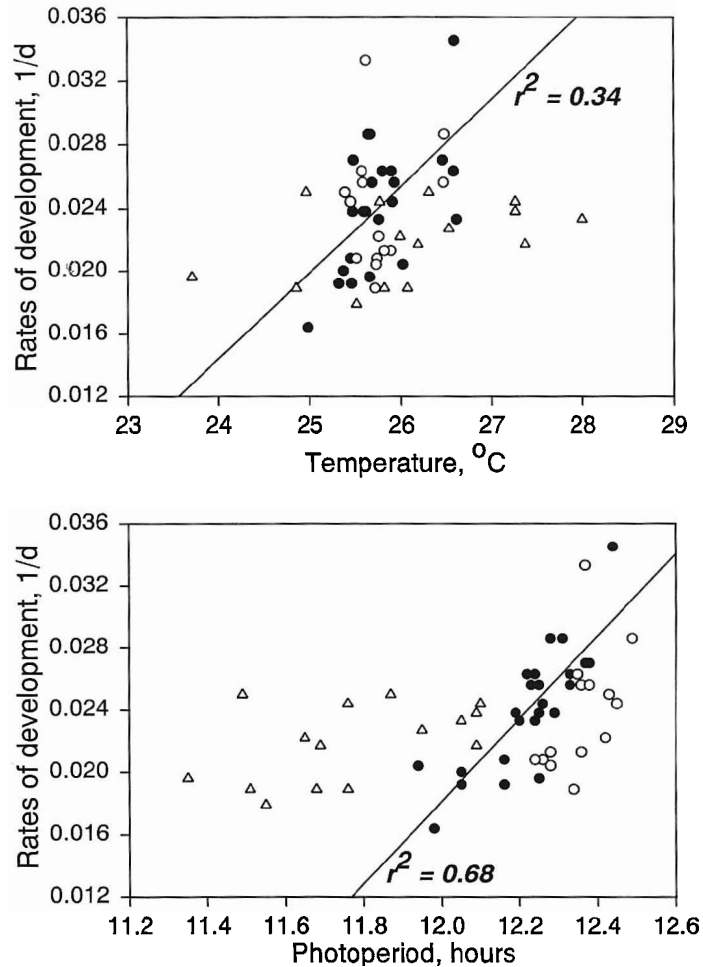


Fig. 4. Effect of temperature (a) and photoperiod (b) on pigeonpea reproductive development rates in ICRISAT (group of cultivars, closed circles, and group of lines, open circles) and in Hissar (triangles). Regression lines and r^2 values describe the data for ICRISAT only. Groups of cultivars and lines are defined in Table 1.

tion, e.g., arabidopsis, are not yet studied well enough for the mechanistic modeling. It appears that in the phenomenon of photoperiod effect, the processes of physical nature play more important role than the biochemical ones. Physical processes related to light effects on plant are often irregular and stochastic. In this situation, we have to use the empirical function, a polynomial, and a goodness of fit as a leading criterion. To make a qualitative adequacy of the model better, one has to increase an order of this function; this, in turn, means increasing a number of model parameters. Then the reliability of the parameter values decreases. A third order of

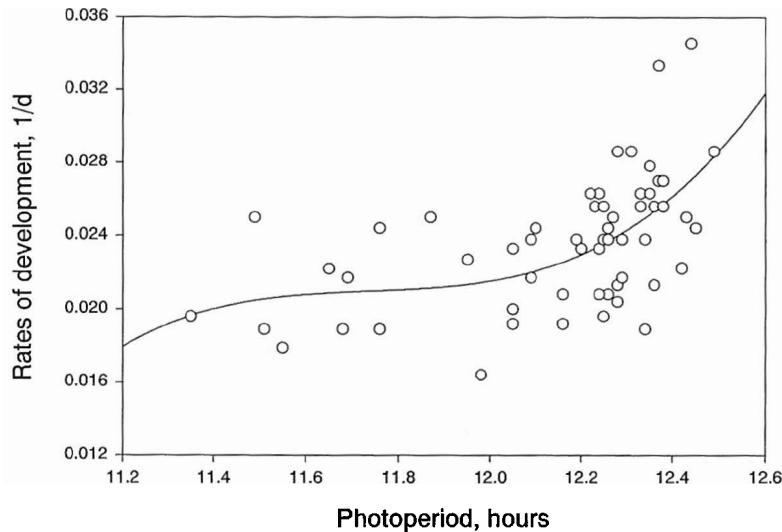


Fig. 5. Nonlinearity of the dependence of pigeonpea reproductive development rates on photoperiod. Points represent the whole set of the experimental data for all locations, years, and genotypes, a line is an approximation of the dependence by cubic function, equation [6].

polynomial was chosen as satisfying the quantitative criterion, and it seems to be a reasonable compromise.

The model for the rates of reproductive development based on this analysis can be presented by the following equation containing 6 parameters:

$$R_{gen} = (G_i + G_3 * PhP + G_4 * PhP^2 + G_5 * PhP^3) * (G_6(T - t_i)) \quad [7]$$

$i=1$ for ICRISAT, $i=2$ for Hissar

Parameter values are presented in Table 5. G_1 and G_2 , the parameters accounting for locations, were significantly different.

Fig. 6 shows the correspondence between measured and calculated rates of reproductive development of pigeonpea which is quite acceptable, $r^2=0.99$. Both models, [5] and [7], for vegetative and reproductive rates of development were estimated for adequacy using the methodology described above. For ICRISAT, Hissar, and El Reno locations, they are adequate.

The model [5] was tested with the data published by Omanga, Summerfield, and Qi (9). In this study, the effects of temperature and photoperiod on duration of vegetative stage of medium- and late-maturing pigeonpea cultivars have been studied in semi-controlled environment experiments in Kenya. The details of the experiment could be found in Omanga *et al.* (9). Duration of the vegetative stage for the six medium-maturing genotypes varied from 70 to 76 days in the most inductive regime (12.6 hours photoperiod, 24.3°C) and it was between 139 to 256 days in the least inductive treatments (15 hours photoperiod and 20.8°C). For this set of data parameters of the model [5] were calculated, $B_1=-0.0797$ for the most inductive regime,

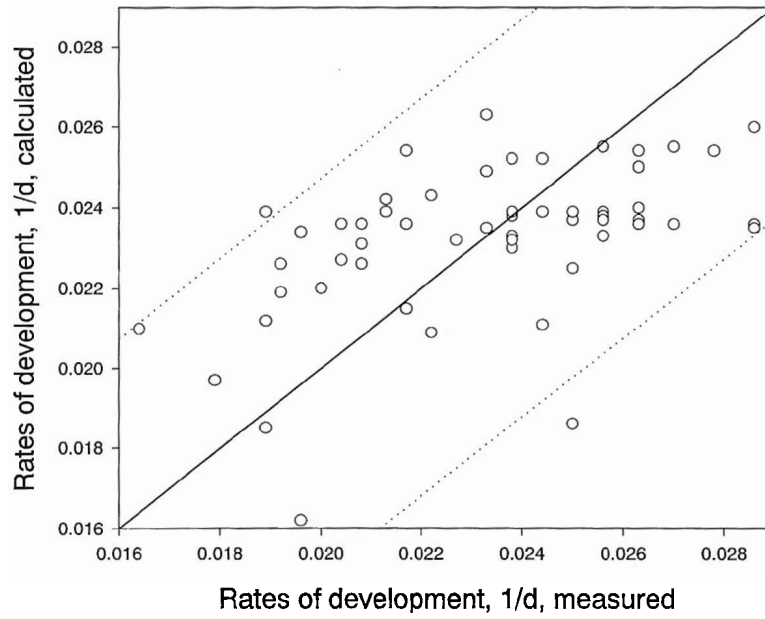


Fig. 6. 1:1 diagram for measured and calculated with the model [7] values of the pigeonpea development rates for the reproductive stage, $r^{2*}=0.55$.

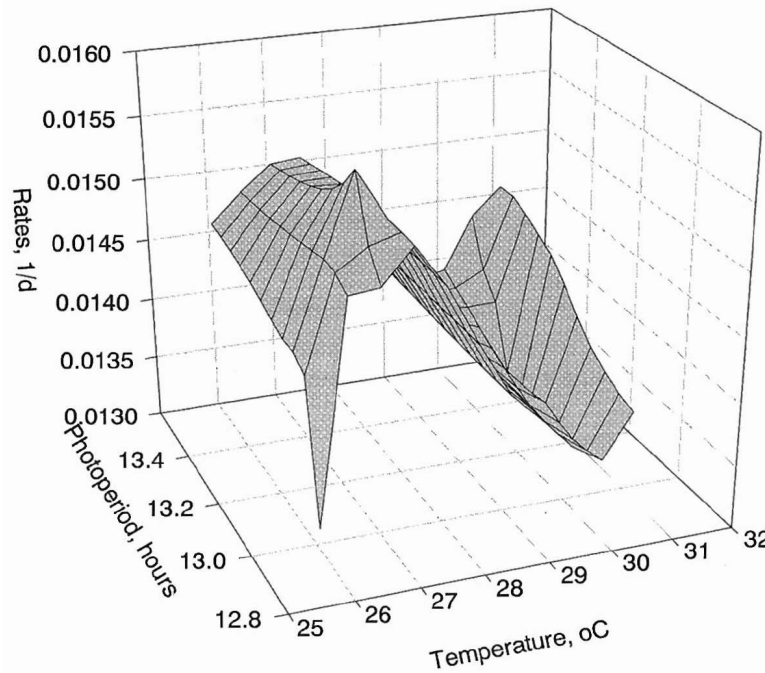


Fig. 7. Measured in ICRISAT rates of vegetative pigeonpea development as a function of temperature and photoperiod.

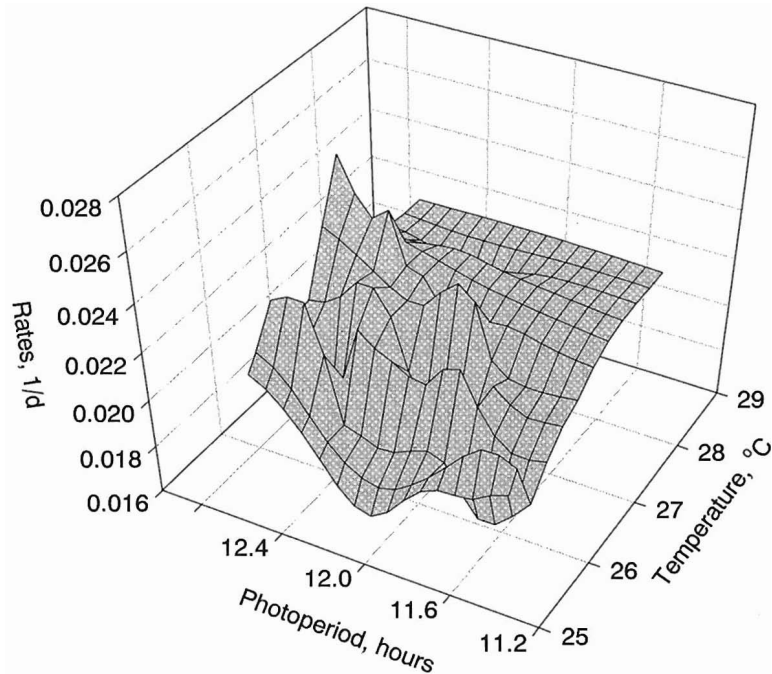


Fig. 8. Measured in ICRISAT rates of reproductive pigeonpea development as a function of temperature and photoperiod.

and $B_2 = -0.096$ for the least inductive one, and $B_3 = 0.0064$. Comparison of rates of vegetative development calculated with the model [5] and measured in the experiments by Omanga *et al.* (9) showed that it was adequate. Model [5] was developed for the early maturing cultivars. Nevertheless, being parameterized for the medium-maturing cultivars grown in semi-controlled environments in Kenya, it is reproduced the measured data with a high quality, $r^{2*} = 0.95$.

Three-dimensional plots in ICRISAT of measured rates of development on temperature and photoperiod, Fig. 7 for the vegetative stage and Fig. 8 for the reproductive period, showed that: (a) the rates strongly and non-linearly depend on both, temperature and photoperiod, (b) these dependencies are different before flowering and during the reproductive stage, and are much more complicated and non-linear for the reproductive period, and there are (c) significant interactions between two factors. Fig. 8 showed that at higher temperature, rates as functions of photoperiod are close to linear dependence, but in a range of temperature between 25 and 28°C, there are strongly non-linear and complex dependences of the development rates on photoperiod. In field conditions, the range in which photoperiod varies are quite narrow during the stage of development, and mathematically these dependencies could be considered linear. But these small variations of photoperiod make significant changes in rates of development, especially during the reproductive growth.

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