

## The response of pigeonpea genotypes of different duration types to variation in temperature and photoperiod under field conditions in Kenya

S.N. Silim<sup>1\*</sup>, R. Coe<sup>2</sup>, P. A. Omanga<sup>3</sup> and E.T. Gwata<sup>1</sup>

<sup>1</sup>International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), P.O. Box 39063, Nairobi 00623, Kenya. <sup>2</sup>International Centre for Research in Agroforestry (ICRAF), P.O. Box 30677, Nairobi, Kenya. <sup>3</sup>National Dryland Farming Research Centre, P.O.Box 340, Machakos, Kenya. \*e-mail: s.silim@cgiar.org

Received 11 September 2005, accepted 17 November 2005.

### Abstract

Field studies were conducted with pigeonpea [*Cajanus cajan* (L.) Millsp.] in Kenya to determine the influence of photoperiod and temperature on flowering. Variation in temperature was achieved by planting six genotypes at four locations varying in altitude where temperature decreased with increase in altitude and variation in photoperiod was achieved through artificial lighting (about 12.6 h – natural day length, 14.5 h and 16.0 h). The genotypes used in the study were carefully selected to represent different duration types (extra-short-, short-, medium- and long-duration) and major pigeonpea production regions. Equations that describe the rates of development ( $1/f$ ) were used to determine rates of progress of each genotype towards flowering as influenced by temperature and photoperiod. For photoperiods below 13 h, rates of progress towards flowering were influenced by temperature in five genotypes (ICPL 90011, ICPL 87091, ICP 7035, ICP 6927 and ICEAP 00040). The optimum temperatures for rapid flowering were 24.7°C for the extra-short-duration genotype, 23.1°C for the short-duration genotype, 23.8°C and 22.2°C for medium-duration genotypes and 18.3°C for the long-duration genotypes, which indicated that the origin of the genotype had a strong influence on adaptation. The effects of photoperiod on rates of progress towards flowering were investigated only under sub-optimal temperatures. The extra-short-duration genotype (ICPL 90011) was the least responsive to variation in photoperiod, while the two long-duration genotypes (ICEAP 00040 and T-7) were most sensitive to photoperiod variation with flowering rate reduced by 0.001 d<sup>-1</sup> per hour increase in day length.

**Key words:** Genotypes, photoperiod, pigeonpea, optimum temperature.

### Introduction

Pigeonpea (*Cajanus cajan* (L.) Millsp.) is one of the major grain legumes grown in the tropics and subtropics. The crop is grown rainfed in drought-prone areas where daylength varies from 11 to 14 h and large differences in temperature are experienced, largely due to variations in altitude and latitude. The traditional varieties grown are mainly medium- and long-duration types. They are intercropped with cereals such as maize (*Zea mays*) and sorghum (*Sorghum bicolor*) and various short-duration legumes such as cowpea (*Vigna unguiculata*) and beans (*Phaseolus vulgaris*)<sup>9</sup>. These traditional genotypes are extremely sensitive to photoperiod and temperature, with plant height, vegetative biomass, phenology and grain yield being the traits most affected<sup>17</sup>. The vegetative phase of development normally coincides with relatively long days and warm temperatures at the higher latitudes and with warm temperatures at lower latitudes<sup>6,7</sup>. Reproductive phase of development coincides with the period when temperatures are cool and daylength is short. Consequently, it is tempting to overlook the effect of temperature and conclude that flowering is triggered only by short days.

The sensitivity of pigeonpea to temperature and photoperiod is a major constraint to development of stable and predictable management practices, cropping systems and genotypes<sup>17</sup>. If sensitivity in phenology leads to a delay in maturity, it is likely to result in yield reduction in those areas where rainfall duration is

short or where the crop depends on residual soil moisture. In areas with a bimodal rainfall, such as Kenya, acceleration of phenology may result in reproductive growth occurring between the two rainfall periods and the crop would thus suffer from drought stress at the time when it is most sensitive. Similarly, where there is accelerated phenology, reproductive growth may coincide with a period of high pest incidence<sup>16</sup>.

Extra-short- and short-duration pigeonpea genotypes developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), escape drought and are relatively less sensitive to photoperiod than traditional varieties with longer growth cycles<sup>12</sup>. This has increased the flexibility of pigeonpea cultivation and facilitated its use in different cropping systems<sup>5</sup>. However, these new genotypes developed by ICRISAT are sensitive to temperature and are not adapted to cool production areas<sup>10</sup>.

The first step towards maximizing yield is to ensure that the phenology of the crop matches the resources of the production environment<sup>8</sup>. A series of photothermal models used to predict phenological events such as time to flowering ( $f$ ) as well as the rate of progress towards flowering ( $1/f$ ) was described<sup>14</sup>. Such models are useful in selecting prospective genotypes for environments that have optimum production conditions. The temperature range in which plant growth and development occurs is characterized by base temperature ( $T_b$ ) below which the rate of

development is zero, an optimum temperature ( $T_o$ ) at which the rate of development is most rapid, and a warmer ceiling limit ( $T_{ce}$ ) beyond which development ceases<sup>8</sup>. In short-day plants such as pigeonpea, flowering response to photoperiod is determined by the critical photoperiod ( $P_c$ ), defined as that daylength which, if exceeded, flowering is delayed. With further increase in daylength, a ceiling photoperiod ( $P_{ce}$ ) is reached when maximum number of days is taken to reach flowering<sup>3</sup>.

There is lack of information on the sensitivity of pigeonpea to temperature and photoperiod under field conditions in the agro-ecological areas in Kenya. Therefore, the objectives of this study were to determine (i) the usefulness of the Kenya transect (varying in altitude from near sea level to 2000 m in altitude) as a tool for screening pigeonpea genotypes for adaptation to prevailing temperatures; (ii) the variability, in response to temperature and photoperiod, in time to flowering ( $f$ ) among the genotypes and (iii) to test the models for predicting phenological events in pigeonpea.

### Materials and Methods

**Genetic material:** Six genotypes were selected carefully to represent the main duration types found in pigeonpea (Table 1). The extra-short- and short-duration genotypes were developed at ICRISAT (Patancheru, Andhra Pradesh, India). They were selected, as representative genotypes for further evaluation, from a study involving 64 extra-short- and short-duration pigeonpea genotypes<sup>10</sup>. The remaining genotypes were selected from 48 genotypes used in the studies reported by Silim *et al.*<sup>11</sup>. The two medium-duration genotypes (ICP 7035 and ICP 6927) originated from contrasting environments (Table 1). ICP 7035 was a selection from a landrace collected in India while ICP 6927 was a collection from Trinidad and Tobago. Similarly, the two long-duration genotypes included in the study were from contrasting

environments with T-7 originating from northern India but ICEAP 00040 originated from Kenya.

**Environments:** The field experiments were conducted in Kenya at five locations varying in altitude from 50 m to about 2100 m and where temperatures decrease with increase in altitude (Table 2). The locations (or experimental sites) covered traditional (Katumani, and Kiboko) and non-traditional (Mtwapa, Kabete and Muguga) pigeonpea growing areas. At the experimental sites, latitude ranged from 4°25' to 1°15'S and the daylength was about 12.6 h.

**Experimental design:** There were three light treatments, natural daylength (about 12.6 h) in all locations, 14.5 h (Kiboko, Katumani and Kabete) and 16 h (Kiboko and Kabete). Exposure of genotypes to longer daylengths was achieved by use of 100 W incandescent bulbs that were suspended 2.0 m above ground and 1.5 m apart. The 14.5 h daylength was achieved through an automatic switch that turned the lights on at 05 h and off at 07 h in the morning and on in the evening at 18 h and off at 19.5 h. The 16 h daylength was achieved by turning the lights on at 05 h and off at 07 h in the morning and on in the evening at 18 h and off at 21 h. The daylength treatments were sited at least 100 m from each other.

Each daylength treatment was designed as a trial. Each trial was conducted using six pigeonpea genotypes planted in a randomized complete block design and replicated three times. At each site, the first planting (for the long rain season) and second planting (for the short rain season) were performed (at the start of the rain seasons) during the first week of April and November respectively. Each genotype was sown in plots consisting of three 5.0 m rows. Extra-short- and short-duration genotypes were planted at 0.4 m between rows and 0.1 m within rows. Medium-duration genotypes were planted at 1.0 m between rows and 0.5 m within rows. Long-duration genotypes were planted at 1.2 m between rows and 0.5 m

**Table 1.** Prevailing agro-ecological conditions at the place of origin for pigeonpea of different duration types exposed to photothermal conditions in Kenya.

Duration type	Genotype	Origin	Agro-ecological conditions		
			Altitude (m)	Latitude	Cropping environment
Extra-short	ICPL 90011	India	500	17° N	- planting is performed just before the summer solstice and flowering occurs in August
Short	ICPL 87091	India	500	17° N	- same as above
Medium	ICP 7035	India	400	26° N	- vegetative growth occurs under warm temperatures and long days but reproductive growth occurs under short days.
	ICP 6927	Trinidad & Tobago	<100	10° N	- warm temperatures and short daylength throughout season
Long	ICEAP 00040	Kenya	1 110	1° 35' N	- vegetative growth occurs under warm temperatures and reproductive growth occurs under cool temperatures - daylength is short throughout the season
	T-7	India	600	28° N	- early vegetative growth occurs under hot temperatures and long days - later vegetative growth occurs under cold temperatures and short days - reproductive growth occurs under cool but rising temperatures and short days

within rows. Sowing was by hand in ploughed and harrowed fields. Three to four seeds were sown in each hill. During planting no fertilizers were used. The seeds were not inoculated with rhizobia. Fourteen days after emergence, seedlings were thinned to one per hill. Weeds were controlled by hand weeding. The plants were protected against insect pests during flowering and post-flowering phases by insecticidal sprays. No mineral deficiency symptoms were observed during crop growth. At Kiboko, the driest location, the trials were maintained as near as possible to field capacity through supplemental irrigation. At the other locations, the crop did not experience water deficit.

**Data collection and analysis:** During the duration of the trials and at all the experimental sites, daily maximum and minimum temperatures were obtained from meteorological stations located within 400 m of all of the experiments. The mean pre-flowering maximum ( $T_{max}$ ) and minimum ( $T_{min}$ ) temperatures for each genotype in each environment were calculated using the daily temperature values from sowing until 50% of the plants in a plot had at least one open flower (flowering). Time to flowering was recorded for each genotype in each replicate. The mean pre-flowering photoperiod for each genotype was calculated from the daily photoperiod between sowing and flowering.

The response to temperature and photoperiod of times from sowing to flowering ( $f$ ) was based on means of the three replications for each genotype-environment. Rates of progress from sowing to flowering were calculated as  $1/f$  (i.e. the reciprocal of the time from sowing to flowering) for each genotype<sup>3,14</sup>. The protocol is based on three well-defined linear relations between  $1/f$  and mean pre-flowering temperature ( $T$ ) and mean pre-flowering photoperiod ( $P$ ). In a crop such as pigeonpea, which is photoperiod sensitive, when daylength is less than critical photoperiod ( $P_c$ ), then  $1/f$  is a positive and linear function of temperature from a base temperature ( $T_b$ ) at which the rate is zero, up to an optimum temperature ( $T_o$ ) at which it is maximal. Between  $T_b$  and  $T_o$ , the relationship is described as:  $1/f = a + bT$  (1)

where the values  $a$  and  $b$  are specific to each genotype; above  $T_o$  the values of the constants are different from those in the sub-optimal range and the relation (i.e., the sign of the parameter  $b$ ) will be negative. Depending on the photothermal environment for a given duration type, additional procedures were applied<sup>6</sup>. In these procedures, the data for each genotype were fitted to equation 2:

$$1/f = a_1 + b_1(T - T_o) + b_2|T - T_o| \quad (2)$$

where  $T_o$  is the apparent optimal temperature to be estimated,  $a_1$  is the apparent maximal rate of progress to flowering when  $T = T_o$ , the parameter constants  $b_1$  and  $b_2$  combine to determine the flowering response to the entire temperature range from  $T_b$  (base) to  $T_c$  (ceiling) and the symbol  $| |$  is the absolute value of the difference between  $T$  and  $T_o$ . Eqn. 2 can be rewritten as:

$$1/f = a_1 + (b_1 - b_2)(T - T_o) \quad \text{for } T < T_o$$

$$1/f = a_1 + (b_1 + b_2)(T - T_o) \quad \text{for } T > T_o \quad (3)$$

where  $a_1$ ,  $b_1$  and  $b_2$  are linear parameters to estimate.  $T_o$  requires non-linear estimation.

In short day plants, there is critical photoperiod ( $P_c$ ) which is the daylength, when exceeded, causes a delay in flowering, and a ceiling photoperiod ( $P_{ce}$ ), longer than  $P_c$  when  $f$  reaches a maximum number of days<sup>14</sup>. The rate of development at a given temperature

within the limits of the  $P_c$  and  $P_{ce}$  is given by:

$$1/f = a' + c'P \quad (4)$$

where  $P$  is daylength (h d<sup>-1</sup>) and  $a'$  and  $c'$  are genotype specific constants of which  $c'$  has a negative value for a short-day plant such as pigeonpea. In addition, a maximum delay is reached at the  $P_{ce}$  above which there is no further delay in flowering in short-day plants and when  $P > P_{ce}$ , a variation in  $P$  or  $T$  has no effect on  $f$ .

In most crops, both temperature and photoperiod modulate progress towards flowering. A combined equation describing variation in rate ( $1/f$ ) in photoperiod-sensitive genotypes between critical and ceiling photoperiods and between the base and optimal temperatures may be described as a response plane given by:

$$1/f = a' + b'T + c'P \quad (5)$$

and the plane of maximum photoperiod delay is given by:

$$1/f = d' \quad (6)$$

where  $a'$ ,  $b'$ ,  $c'$  and  $d'$  are genotype specific constants.

We had insufficient data at the supra-optimal temperature range for determining the influence of photoperiod at varying temperature. Consequently, the effect of photoperiod on  $f$  was analysed at the sub-optimal temperature range only.

## Results

Mean temperatures experienced in each of the ten environments created by locations and seasons indicated that the plants were exposed to different temperatures during both pre-and post-flowering development phases (Table 2). The post-flowering temperatures were cooler than the pre-flowering temperatures during the long rain season (for the crop sown in April,) but warmer during the short rain season (for the crop sown in November). Medium- and long-duration genotypes experienced cooler temperatures during the reproductive phase at Kiboko, Katumani, Kabete and Muguga (Table 2).

There were large variations across the environments for mean  $f$  (Table 3). Both the extra-short and short-duration genotypes flowered within 100 days from sowing but the medium- and long-duration genotypes flowered later. For photoperiod < 13 h, rates of progress towards flowering in five genotypes (ICPL 90011, ICPL 87091, ICP 7035, ICP 6927 and ICEAP 00040) were affected by temperature (Table 4). The extra-short duration genotype (ICPL 90011) had the highest optimum temperature while the long-duration genotype ICEAP 00040 had the lowest optimum temperature. The long duration genotype (T-7), which originated from northern India (where temperatures vary from sub-zero to > 40°C during the growing season), was insensitive to temperature in the range tested.

There was no clear pattern in the slopes of the response of different genotypes to temperature (Fig. 1). However, at sub-optimal temperatures, the genotypes originating from warm environments (ICPL 90011, ICPL 87091 and ICP 7035) relatively, were more sensitive to temperature in the range tested.

There was insufficient data at the supra-optimal temperature range to develop models for response to photoperiod under the range sub-optimal to supra-optimal temperature. As a result, response to photoperiod was analysed using the model in equation (4) fitted to data from sub-optimal temperatures only (Table 5). The genotype ICPL 90011 was insensitive to daylength changes but the long-duration genotypes (ICEAP 00040 and T-7) showed a strong response, with flowering rate reduced by 0.001 d<sup>-1</sup> per hour increase in daylength.

**Table 2.** Latitude, altitude, long- term mean temperatures and seasonal rainfall for the locations (study sites) in Kenya.

Location	Latitude (South)	Altitude (m)	Soil type	Season <sup>a</sup>	Temperature (°C)			Rainfall (mm)
					Max.	Min.	Mean	
Mtwapa	4°25'	50	Deep sandy	SR	31.4	23.2	27.3	370
			clay loam	LR	28.9	21.5	25.2	679
Kiboko	2°20'	900	Sandy clay	SR	29.4	17.7	23.5	464 <sup>b</sup>
			loam, calcareous	LR	27.8	15.5	21.6	140 <sup>b</sup>
Katumani	1°35'	1560	Very deep, sandy	SR	25.6	14.4	20.0	467
			loam to clay	LR	23.6	12.9	18.2	244
Kabete	1°15'	1825	Extremely deep	SR	24.6	12.9	18.7	478
			friable clay	LR	22.1	12.2	17.1	518
Muguga	1°15'	2095	Extremely deep	SR	22.0	11.5	16.8	462
			friable clay	LR	19.4	10.2	14.9	442

LR - Long rain season (from end of April to mid-September)

<sup>a</sup>SR - Short rain season (from end of October to mid-February)

<sup>b</sup>Received supplemental irrigation

**Table 3.** Mean number of days to flowering of six pigeonpea genotypes grown at different locations in Kenya under natural daylength.

Location	Genotype					
	ICEAP 00040	T-7	ICP 6927	ICP 7035	ICPL 87091	ICPL 90011
Muguga	156	170	160	-	-	-
Kabete	149	150	123	119	91	80
Katumani	178	185	105	94	81	78
Kiboko	227	164	121	125	74	64
Mtwapa	300	-	119	122	84	79

- Missing data

**Table 4.** Estimates of parameters of equation 3 and coefficient of determination ( $R^2$ ) for six pigeonpea genotypes grown under varying temperatures in Kenya.

Genotype	Intercept ( $10^{-3}$ )		Slope ( $10^{-3}$ )				Optimum temperature		$R^2$
	a	S.E.	$(t < T_0)$		$(t > T_0)$		$T_0$	S.E. $T_0$	
			$b_1 - b_2$	S.E.	$b_1 + b_2$	S.E.			
ICPL 90011	17.55	0.73	0.81	0.13	-3.9	1.45	24.70	0.28	0.80
ICPL 87091	16.05	0.44	0.97	0.67	-1.57	0.58	23.10	1.29	0.52
ICP 7035	14.55	1.15	1.25	0.49	-1.79	0.36	22.20	0.68	0.71
ICP 6927	12.22	0.39	0.53	0.08	-2.26	0.37	23.80	0.29	0.90
ICEAP 00040	8.40	0.20	0.34	0.10	-0.63	0.05	18.30	0.39	0.94
T-7*	7.14	-	-	-	-	-	-	-	0.00

\*Insensitive to the temperature range tested.

**Table 5.** Estimates of parameters  $a'$ ,  $b'$  and  $c'$  and coefficient of determination ( $R^2$ ) for six pigeonpea genotypes grown under varying photoperiod at sub-optimal temperature (derived from equation 5) in Kenya.

Genotype	Parameter ( $\times 10^{-3}$ )			$R^2$
	$a'$	$b'$ (S.E. $b'$ )	$c'$ (S.E. $c'$ )	
ICPL 90011	-4.45	0.80 (0.13)	-0.18 (0.27)	0.79
ICPL 78091	0.12	0.96 (0.48)	-0.50 (0.29)	0.36
ICP 7035	4.70	0.84 (0.61)	-0.83 (0.29)	0.35
ICP 6927	13.73	0.34 (0.12)	-0.87 (0.21)	0.56
ICEAP 00040	15.14	0.33 (0.17)	-1.01 (0.24)	0.70
T-7	24.39	-0.18 (0.12)	-1.08 (0.27)	0.58

### Discussion

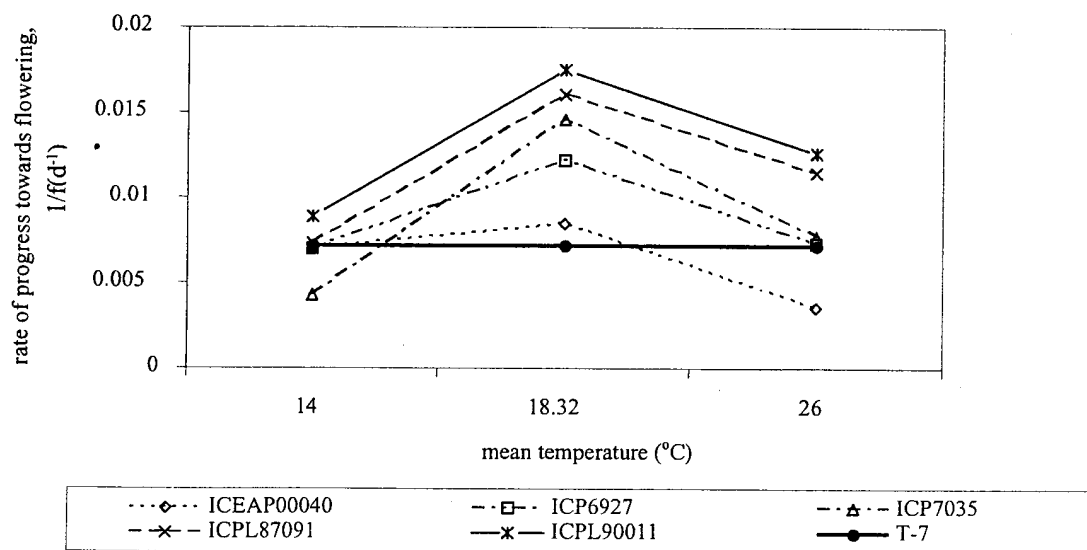
The six pigeonpea genotypes used in this study were selected carefully in order to represent the four duration types (extra-short-, short-, medium- and long-duration) as per ICRISAT classification and the major pigeonpea agro-ecologies in Kenya. The extra-short- and short-duration genotypes had high optimum temperature for time to flower with cool temperatures lengthening and warm temperatures shortening the duration. This observation was consistent with findings reported in similar studies<sup>4, 10, 11, 15</sup>. For medium-duration genotypes, the differences in optimum temperature for time to flower between the two genotypes indicated their adaptation to area of origin. ICP 6927 originated from lowland areas near the equator where temperatures are high and with low seasonal variability, while ICP 7035 is from low elevation areas where temperatures during the vegetative stages are high but low during the reproductive phases. By contrast, the long-duration genotype (T-7) was insensitive to variation in temperature likely because it is a landrace from northern India where temperatures during the crop's growth cycle vary from  $>40^\circ\text{C}$  to sub-zero.

In spite of the small sample size, the results from this study also

indicated that adaptation for pigeonpea can be classified into three broad categories namely 1) genotypes bred in (or evolved from) areas with high temperatures (e.g. ICPL 90011, ICPL 87091, ICP 6927) have high optimum temperature for  $f$  (with low temperatures delaying  $f$ ), 2) genotypes from medium altitude areas (e.g. ICEAP 00040) where mean temperatures vary from warm ( $21^\circ\text{C}$ ) to cool ( $17^\circ\text{C}$ ), have low optimum temperatures  $f$  (with high temperatures delaying or inhibiting  $f$ ), and 3) genotypes that originated in areas where variation in temperatures are large (e.g. T-7) are insensitive to temperature in terms of  $f$ .

This study also showed that with the exception of genotypes from northern India, pigeonpea has specific and narrow adaptation. In barley, breeding either for narrow or wide adaptation was suggested<sup>2</sup>. Knowledge of the environment where the genotypes are bred (or originate) would be useful in designing pigeonpea breeding programs and selecting genotypes for cultivation in specific optimum environments.

For photoperiod, the long duration genotypes (ICEAP 00040 and T-7) were the most sensitive, followed by medium-duration genotypes (ICP 6927 and ICP 7035), which were intermediate in



**Figure 1.** Relationship between  $1/f$  and mean temperature to 50% flowering of six pigeonpea genotypes varying in duration and origin and growing in different locations in Kenya under natural (12 or 12.6 h) daylength.

sensitivity. The short-duration genotype (ICPL 87091) was insensitive and extra-short-duration genotype (ICPL 90011) was the least sensitive to photoperiod. In similar studies, medium- and long-duration cultivars delayed flowering by 150 days in response to photoperiod<sup>1</sup>. In our study, the observed lack of sensitivity in these genotypes could be attributed to their place of origin in India, where planting is carried out during the longest days in June, and flowering occurs at the beginning (for ICPL 90011) and end (for ICPL 87091) of August under long but progressively decreasing days.

In most countries in eastern Africa, long-duration types of pigeonpea are intercropped with maize. In cool areas, severe competition occurs between intercropped maize and pigeonpeas resulting in yield reduction of both crops. Therefore, we propose the development, through plant breeding, of long-duration cultivars that mature later than the current traditional long-duration genotypes. Secondly, current medium-duration genotypes from the equatorial region mature 50 to 100 days earlier than the long-duration types. However, because of their sensitivity to photoperiod, the current medium-duration genotypes tend to mature late when grown in areas away from the equator, such as Malawi and thus suffer from terminal drought stress. In our view, it is necessary to introgress insensitivity to photoperiod but maintain high optimum temperatures in these genotypes in order to use them in areas away from the equator.

## References

- <sup>1</sup>Carberry, P.S., Ranganathan, R., Reddy, L.J., Chauhan, Y.S. and Robertson, M.J. 2001. Predicting growth and development of pigeonpea: flowering response to photoperiod. *Field Crops Res.* **69**: 151-162.
- <sup>2</sup>Ceccarelli, S. 1989. Wide adaptation: How wide? *Euphytica* **40**:197-205.
- <sup>3</sup>Keatinge, J.D.H., Qi, A., Wheeler, T.R., Ellis, R.H., Crauford, P.Q. and Summerfield, R.J. 1996. Photothermal effects on phenology of annual legume crops with potential for use as cover crops and green manures in tropical and subtropical hillside environments. *Field Crops Abstr.* **49**:119-1130.
- <sup>4</sup>McPherson, H.G., Warrington, I.J. and Turnbull, H.L., 1985. The effects of temperature and daylength on the rate of development of pigeonpea. *Ann. Bot.* **56**:597-611.
- <sup>5</sup>Nene, Y.L. 1991. Pigeonpea research: future research strategies in Africa. In Laxman, S., Silim, S.N., Ariyanayagam, R.P. and Reddy, M.V. (eds). *Proc. First East. South. Afr. Reg. Legumes (Pigeonpea) Workshop*. ICRISAT Publ., Patancheru, pp. 1-4.
- <sup>6</sup>Omanga, P.A., Summerfield, R.J. and Qi, A. 1995. Flowering of pigeonpea (*Cajanus cajan*) in Kenya: Responses of early-maturing genotypes to location and date of sowing. *Field Crops Res.* **41**:25-34.
- <sup>7</sup>Reddy, S.J. and Virmani, S.M. 1981. Pigeonpea and its climatic environments. *Proc. Int. Workshop Pigeonpea*. ICRISAT Publ., Patancheru, pp. 259-270.
- <sup>8</sup>Richards, R.A. 1989. Breeding for drought resistance-physiological approaches. In Baker, F.W.G. (ed.). *Drought Resistance in Cereals*. CAB International, pp. 65-79.
- <sup>9</sup>Silim, S.N., Johansen, C. and Chauhan, Y.S. 1991. Agronomy of traditional and new cropping systems of pigeonpea and potential for Eastern Africa. In Laxman, S., Silim, S.N., Ariyanayagam, R.P. and Reddy, M.V. (eds.). *Proc. First East. South. Afr. Reg. Legumes (Pigeonpea) Workshop*. ICRISAT Publ., Patancheru, pp. 17-30.
- <sup>10</sup>Silim, S.N. and Omanga, P.A. 2001. The response of short-duration pigeonpea lines to variation in temperature under field conditions in Kenya. *Field Crops Res.* **72**:97-108.
- <sup>11</sup>Silim, S.N., Omanga, P.A., Johansen, C., Laxman, S. and Kimani, P.M. 1995. Use of the Kenya transect for selecting and targeting adapted genotypes to appropriate production systems. In Silim, S.N., King, S.B. and Tuwafe, S. (eds). *Improv. Pigeonpea East. South. Afr. - Ann. Res. Plan. Meet.* 1994. ICRISAT Publ., Patancheru, pp. 44-54.
- <sup>12</sup>Singh, L., Gupta, S.C. and Faris, D.G. 1990. Breeding. In Nene, Y.L., Hall, S.D. and Sheila, V.K. (eds). *The Pigeonpea*. CAB International, pp. 375-400.
- <sup>13</sup>Summerfield, R.J., Lawn, R.J., Qi, A., Ellis, R.H., Roberts, E.H., Chay, P.M., Brouwer, J.B., Rose, J.L., Shanmugasundaram, S., Yeates, S.J. and Sandover, S. 1993a. Towards the reliable prediction of time to flowering in six annual crops. II. Soybean (*Glycine max*). *Exp. Agric.* **29**:253-289.
- <sup>14</sup>Summerfield, R.J., Lawn, R.J. Roberts, E.H. and Ellis, R.H. 1991. Towards the reliable prediction of time to flowering in six annual crops. 1. The development of simple models for fluctuating field environments. *Exp. Agric.* **27**:11-31.
- <sup>15</sup>Turnbull, L.V. and Ellis, E.H. 1987. Effect of incandescent and fluorescent lighting used in photoperiod extension on the vegetative growth and floral development of four lines of pigeonpea. *Field Crops Res.* **17**:25-36.
- <sup>16</sup>Wallis, E.S., Byth, D.E. and Whiteman, D.C. 1981. Mechanised dry seed production of pigeonpea. *Proc. Int. Workshop Pigeonpea*. ICRISAT Publ., Patancheru, pp. 50-61.
- <sup>17</sup>Whiteman, E.S., Byth, D.E. and Wallis, E.S. 1985. Pigeonpea [*Cajanus cajan* (L.) Millsp.]. In Summerfield, R.J. and Ellis, R.H. (eds). *Grain Legume Crops*. CPTB, London, pp. 658-698.