Temperature effects on seed germination in races of common beans (*Phaseolus vulgaris* L.)

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ABSTRACT. Temperature is one of the most important environmental factors, affecting establishment and crop development. Seed germination is particularly affected by temperature. The aim of this work was to evaluate the tolerance temperatures during germination in several bean cultivars. The seeds were submitted to temperatures ranging from 8 to 45°C in thermal block apparatus and primary root protrusion time. The number of germinated seedlings was scored for each cultivar and temperature. High temperatures (≅40°C and upper) strongly inhibit cultivar germination, but 'IAPAR-57', 'Guarumbé' and 'Iratim' appear to be more sensitive to high temperature stress than others. 'IAC Carioca 80SH' PP and 'IAPAR-57' were less tolerant to low temperatures. The thermal time model could describe, relatively well, the time-course of the cultivars isothermal germination, which differed in the thermal time amount required to germinate. 'IAC Carioca-Akytã' needs fewer degrees per day to achieve germination than others, whereas the cultivar 'Campeão-1' requires more thermal time.

Key words: bean, cardinal temperature, degrees per day, germinability, velocity.

RESUMO. Efeitos da temperatura na germinação de sementes em culturas de feijões comuns (*Phaseolus vulgaris* L.). A temperatura é um fator ambiental importante, afetando a germinação de sementes, o estabelecimento e o desenvolvimento de culturas. O objetivo deste trabalho foi avaliar as temperaturas de tolerância durante germinação em vários cultivares de feijão e determinar o valor de parâmetros térmicos para a germinação de cultivares. Sementes foram submetidas a temperaturas variando de 8°C a 45°C, em bloco termo-gradiente até a protrusão da raiz primária. Temperaturas altas (40°C ou mais) inibem fortemente a germinação dos cultivares. 'IAPAR-57, 'Guarumbé' e 'Iratim' parecem ser mais sensíveis à temperatura alta que outros. 'IAC Carioca 80SH ' PP e 'IAPAR-57' foram menos tolerantes a baixas temperaturas. O modelo termal de tempo poderia descrever relativamente bem o curso da germinação em isotermas dos cultivares que diferiram na quantia de graus-dia para germinar. 'IAC Carioca-Akytã' precisa de menos graus-dia^{-1} para alcançar a germinação que outros, O cultivar' Campeão-1 requer mais graus-dia^{-1}.

Palavras-chave: feijão, temperatura cardeal, graus por dia, germinabilidade, velocidade.

Introduction

The large genetic diversity in common bean races is followed by adaptations to different environments (Delgado *et al.*, 1988). Temperature is one of the most important environmental factors, affecting crops' establishment and development. Seed germination is particularly affected by temperature, which is widely reported in scientific literature. In general seed pattern, germination increases as temperature rises from a minimum (or base) to an "optimum" temperature or temperature range, then germination declines with increasing temperatures up to a "maximum" or "ceiling", above which the seeds do not germinate. Minimum and maximum are the limit temperatures for seed germination, and these characteristics depend on the species, lot, seed dormancy, etc. Thus, different seed lots can be characterized by their cardinal temperatures, that is, the base, the optimum, and the maximum temperature (Labouriau, 1983).

As pointed by White and Montes (1993), the study of temperature dependence at seed germination in common bean is interesting for many reasons, such as: i) genotype selection for improved germination at low or high temperatures; ii) modelling crop development in response to air or soil temperature regime and iii) to understand bean phylogeny and evolution. Although the response of *Phaseolus vulgaris* plants to temperature may vary depending on the development stage and specific process (Franco *et al.*, 1972), correlations of field and laboratory measurements of germination responses to different temperatures have been examined in several leguminous crop species. In alfalfa, for example, rapid germination and primary root growth at suboptimal temperatures in laboratory was positively correlated with high emergence at field conditions (Klos and Brummer, 2000). In soybean and common bean, the germination rate under low temperatures in the laboratory provided a good tolerance test for cold field conditions (Dickson and Boettger, 1984). Kolasinska *et al.* (2000) observed that soil temperature at sowing appeared to be the most important environmental factor influencing field emergence of common bean, allowing the differentiation of a seed lot with high field emergence potential.

Several authors have investigated the temperature effect on *Phaseolus vulgaris* seeds germination (Roeggen, 1987; Hucl, 1993; Zaiter *et al.*, 1994; Otubo *et al.*, 1996); the conclusions drawn from such investigations were: bean cultivars may have different reactions to temperature; seed germination of common bean under suboptimal temperatures have been strongly influenced by genotype, and some genotypes have been more tolerant to cold during germination than others.

When the relation between germination rate and temperature is linear, thermal time (or heat units) can be used to compare germination in different species (Garcia-Huidobro *et al.*, 1982). According to this model, once the total thermal time to germination is known, and the base temperature is identified, the time to germination at any sub-optimal temperature can be predicted, or germination time courses at a range of suboptimal temperatures can be normalized on a common thermal time scale (Bradford, 1995). Several other approaches focus on temperature dependence of seed germination, such as the analysis of the frequency of germination distributions, as affected by temperature, and the synchronization indexes associated to it (Labouriau and Agudo, 1987).

In the present paper, seed germination of several *Phaseolus vulgaris* cultivars were compared, in order to evaluate their response to different constant temperatures and to determine the values of some thermal parameters for cultivar germination.

Material and methods

Plant material

The following common bean (*Phaseolus vulgaris* L) cultivars were assayed: 'Rosinha G-2'; 'IAC-Carioca-80SH'; 'Vermelho 2157'; 'IAPAR- 57'; 'Rudá'; 'Aporé'; 'Campeão-1', and 'IAC-Carioca-Akytã' . The landraces Iratim and Guarumbé were also tested. The seeds were returned from the germplasm collection of the Cenargen/Embrapa (Centro Nacional de Recursos Genéticos da Empresa Brasileira de Agropecuária, Brasilia, DF), IAC (Instituto Agronômico de Campinas, São Paulo State), and Iapar (Instituto Agronômico do Paraná, Londrina, Paraná State), and they were propagated at the experimental garden of Instituto de Biociências, Universidade Estadual Paulista (Unesp), Rio Claro, São Paulo State. The cultivar 'IAC-Carioca-80SH' was also propagated at Unoeste, Presidente Prudente, São Paulo State, and that lot is hereinafter referred as to 'IAC-Carioca 80SH' PP, in contrast to the lot produced at Rio Claro, referred as to 'IAC-Carioca 80SH' RC. The seeds collected were treated with phosphine and stored in paper bags in acclimatized room (25 ± 2°C) during four months at 50% of UR.

Germination assays

The isothermal incubation was carried out on polypropylene trays lined with thick qualitative filter-paper strips saturated with distilled water and placed inside closed glass tubes (250 x 25 mm) in a temperature gradient block adapted from Labouriau and Agudo (1987). The block is made of ten vertical sets of aluminium tubes, and each set is a temperature station with five replicates. Thus, every temperature station contained five tubes with 30 seeds per tube. The temperature in the thermal stations was measured with PT100 thermistors, connected to an electronic thermometer JK model SK 010 (JK Instrumentos, Piracicaba, São Paulo State). The temperature measurements precision was 0.1°C. Temperature readings of all stations were taken before each observation of the germination tubes, and fluctuations of the mean temperature in each thermal station ranged from 0.1-1°C. Prior to the counting, the tubes were removed from the respective thermal station and the plastic trays were pulled out of the tubes, allowing the seeds to be examined under diffuse white light. As soon as the germination was recorded (2-5 minutes), the seeds were returned to the thermal-gradient block.

The assays were kept in darkness and germination scored at 24-h intervals; seeds were considered germinated once the primary root emerged and achieved geotropic curvature (Labouriau, 1983). The seeds were withdrawn as soon as recorded.

Analysis data

Germinability and germination rate

The final percentage of germinated seeds (germinability, G) was transformed in angular values and compared through analysis of variance. The LSD5% was calculated for the significant differences according to the Tukey's test (Sokal and Rohlf, 1995).

The germination rate was computed as the reciprocal of the average germination time (t), with $t = \Sigma(n_i.t_i)/\ \Sigma(n_i)$, where n_i is the number of germinated seeds between two consecutive observations t_{i-1} and t_i (Labouriau, 1983). Germination rates were compared by stepwise exhaustive comparisons of isotherm pairs (two-tailed Wilcoxon test) (Sokal and Rohlf, 1995). The distributions of isothermal germination frequencies (fi) were computed from the formulae $f_i = n_i/\Sigma n_i$. The synchronization index (U, in bits) was computed as $U = -\Sigma f_i.log_2 f_i$, (Labouriau and Agudo, 1987). The optimum temperature was the one at which both highest germinability and germination rate were observed.

T-base and thermal time calculation

For each line, the isothermal replicates were pooled and mean cumulative germination percentages were plotted against time. The isotherms were subsequently fitted by Weibull function (Dumur *et al.*, 1990):

$$y = M[1 - \exp^{(-k(t-z)c)}]$$

Where: y = cumulative germination at time t; M = maximum germination; k = germination rate; z = lag in germination time; and c = shape parameter.

Times to 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% were obtained from such a function by calculation at each temperature. The rate of germination was, then, modelled, based on concepts developed by Garcia-Huidobro *et al.* (1982); therefore, in suboptimal temperature range, a thermal time (or degrees-day) approach can be used to find the germination times at different suboptimal temperatures:

$$\theta g = (T - Tb)/tg \therefore 1/tg = (T - Tb)/\theta g$$

where: θg = amount of thermal time to complete germination of a given fraction (e.g., 50%); T = temperature; Tb = base temperature; and tg = time to complete germination of a percentage g (Bradford, 1995; Grundy *et al.*, 2000).

Thus, the reciprocal of the times to germination (GR) for the different percentages (10% to 90%) estimated as described above were plotted against T to estimate θg (the reciprocal of the slope of the linear regression of GR on T) and Tb (the intercept on the temperature axis). Then, in order to find a common Tb to each cultivar, all the 1/tg values were regressed on temperature and different values of Tb (temperature value when 1/tg = 0) were tried, until the highest correlation coefficient was obtained. This value was, then, used to calculate θg for each germination record, according to equation above, producing the points at Figure 5 (G% x θg). The curves displayed in the Figure 6 were obtained from the actual measured values of thermal time (θ_T, the slopes of the relationship between 1/tg and T). The θ_T values calculated for a given germination percentage (10% to 90%) were transformed to log and plotted against probit G%, with log θ_T in the abscissa:

$$probit(G\%) = 5 + 1/\sigma(\theta T - \mu) \text{ (Finney, 1952)}$$

Where: σ and μ are respectively the standard deviation (the reciprocal of the slope of the regression of probit(G%) on T) and mean (temperature corresponding to probit = 5) of the θ_T distribution.

At temperatures above the optimum, the amount of points was not enough to try a thermal time approach. Thus, confidence intervals (α = 0.05) were determined for G%, in order to search for the upper temperature limit, in which the confidence intervals intercept the temperature axis (Labouriau and Osborn, 1984).

Results and discussion

Germinability and germination rate (reciprocal of the average time) values for nine isotherms are displayed in Figure 1. The germination was null at the highest temperatures (39.3 and 44.4°C), as well as at 8.3°C. The cultivar 'Vermelho 2157' germinated at 8.3°C, although this germination was insignificant when compared to cultivars from temperate regions such as 'Volare' and 'G.N. Tara', that germinate well at 8°C (Zaiter *et al.*, 1994).

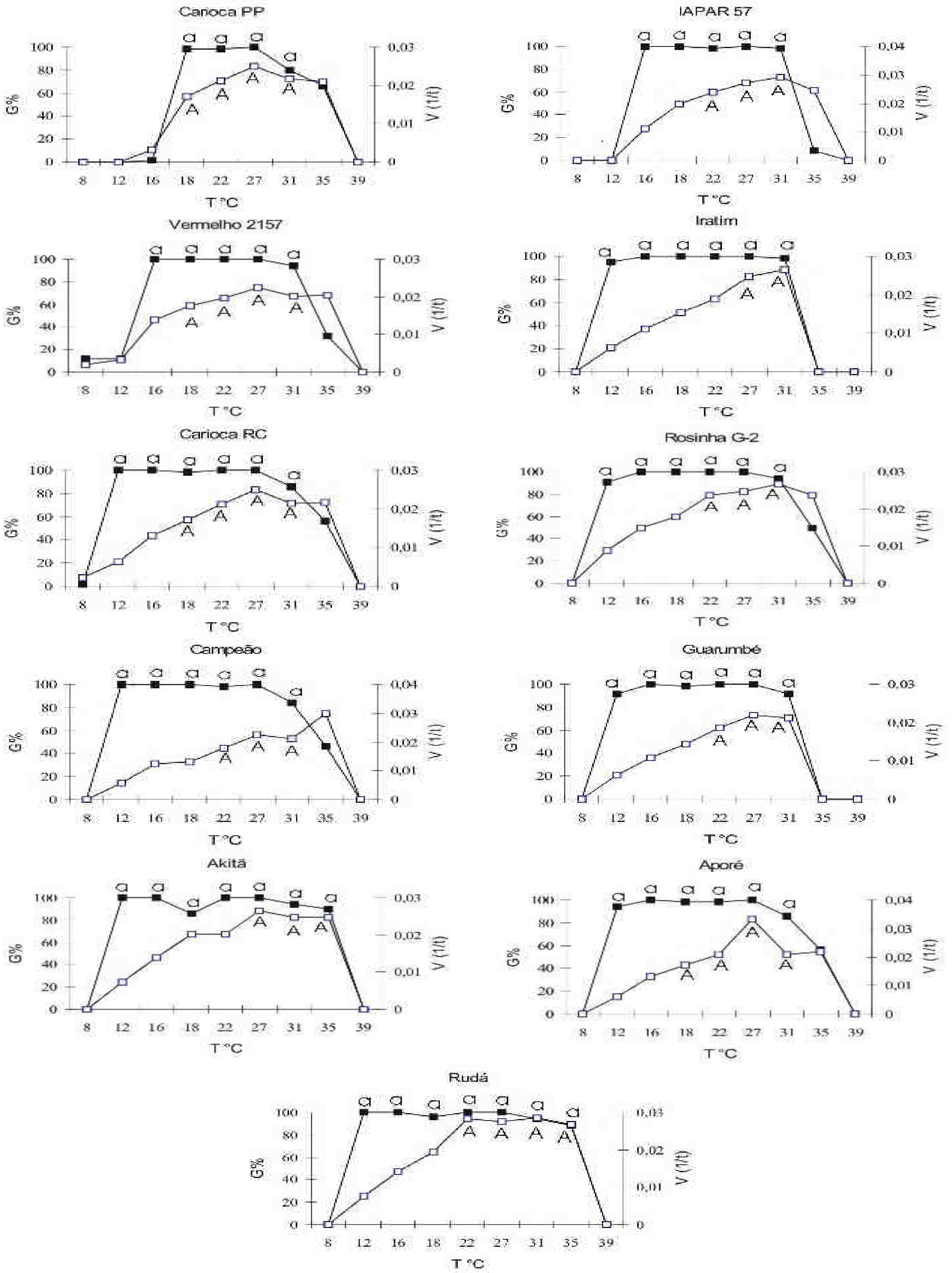

Figure 1. Germinability (dark squares) and germination rate (open squares) temperature dependence of different cultivars of *Phaseolus vulgaris*. Germination rate is the reciprocal of the average time to germination. Capital letters indicate optimum temperatures for germinability; small letters indicate the highest germination rate values within the optimum range of germinability.

The germination optimum range, which means the temperatures at which germination is faster (Bradford, 2002) and germinability, higher, was 18 to 31°C for cultivars 'IAC Carioca 80SH', 'Vermelho 2157' and 'Aporé'; and 22 to 31°C for cultivars 'Rosinha G2', 'IAPAR-57', Guarumbé, and 'Campeão-1' (Table 1). For the cultivars 'IAC Carioca-Akytã' and 'Rudá' the optimum interval to germination ranged from 27 to 35°C and 22 to 35°C, respectively. The widest temperature interval of optimum germination was observed in the cultivars 'IAC-Carioca 80SH', 'Vermelho 2157', 'Rudá', and 'Aporé' (13°C), whereas the narrowest interval containing the optimum isotherms occurred in the cultivar Iratim.

On the other hand, germination rates exhibited higher temperature dependence than germinability. The germination rate tended to linearly increase with the temperature marked in the infra-optimum range. In the supra-optimum interval, rates dropped with temperature at a faster pace than increase rates with rising temperature. A similar pattern is shared by several species, such as tomato (Labouriau and Osborn, 1984) and Indian gherkin (Santos and Cardoso, 2001).

The calculation of the maximum temperature (T_M) to cultivars germination was difficult, due to the relatively sharp decrease in the germination percentage at high temperatures, thus the upper germination temperature limits of the bean cultivars studied here were represented by temperature intervals of nearly 4°C (Table 1). In order to find a maximum temperature, the criterion adopted for T_M is the highest temperature in which the confidence intervals ($p = 0.05$) of germinability intercept the temperature axis ($G = 0\%$) (Labouriau and Agudo, 1987). The cultivars did not differ much from each other concerning T_M interval, which ranged from 35 to 39°C, with exception of the cultivars 'IAPAR-57', Guarumbé and Iratim, whose Tm was between 31 and 35°C (Table 1). It was also observed that temperatures around and higher than 40°C had deleterious effects on the seeds. This agrees with Pena-Valdivia *et al.* (2002) who, working with common bean cultivars from México, reported that high temperatures (35–45°C) have a positive effect on germination breaking of wild cultivars dormancy, but deteriorated the seeds of domesticated lines which did not exhibit dormancy.

Since germination tended to be progressively delayed at temperatures below 27°C in all cultivars, the thermal interval from 12.5 to 22°C was taken as the "sub-optimum" range and employed to find the base temperature (Tb) in each cultivar. The germination time courses of the isotherms in the infra-optimum range were fitted through Weibull function of parameters M, k, z, and c (see Material and Methods), whose values are in Table 2. Values of c around 3.6 suggest that the germination frequency distribution is symmetrical, while higher or lower values indicate negatively or positively skewed distribution, respectively (Bahler *et al.*, 1989). Thus, taking into account the values of the shape parameter c, the cumulative germination curves show deviations from normality, and germinations are concentrated in the left-hand of the overall mode, chiefly at 16, 18, and 22°C. The lag in germination (parameter z) decreases as temperature rises, which means that germination is delayed at lower temperatures.

Table 1. Experimental cardinal temperatures for seed germination of different cultivars of *Phaseolus vulgaris* (T_o – optimum temperature; T_M – maximum temperature; T_m.- minimum temperature).

Cultivar	temperature range (°C)		
	minimum	Optimum	maximum
'IAC-Carioca-80SH' RC	$8 \leq T_m < 13$	$18 < T_o \leq 31$	$35 < T_M \leq 39$
'IAC-Carioca-80SH' PP	$16 \leq T_m < 18$	$18 < T_o \leq 31$	$35 < T_M \leq 39$
'Rosinha G2'	$8 \leq T_m < 13$	$22 < T_o \leq 31$	$35 < T_M \leq 39$
'IAC-Carioca-Akytã'	$8 \leq T_m < 13$	$27 < T_o \leq 35$	$35 < T_M \leq 39$
'IAPAR-57'	$13 \leq T_m < 16$	$22 < T_o \leq 31$	$31 < T_M \leq 35$
Guarumbé	$8 \leq T_m < 13$	$22 < T_o \leq 31$	$31 < T_M \leq 35$
Iratim	$8 \leq T_m < 13$	$27 < T_o \leq 31$	$31 < T_M \leq 35$
'Vermelho-2157'	$8 \leq T_m < 13$	$18 < T_o \leq 31$	$35 < T_M \leq 39$
'Campeão-1'	$8 \leq T_m < 13$	$22 < T_o \leq 31$	$35 < T_M \leq 39$
'Rudá'	$8 \leq T_m < 13$	$22 < T_o \leq 35$	$35 < T_M \leq 39$
'Aporé'	$8 \leq T_m < 13$	$18 < T_o \leq 31$	$35 < T_M \leq 39$

Table 2. Parameters M, k, z, and c, describing the germination time courses for *P. vulgaris* cultivars fitted by Weibull function at different constant temperatures (12.5°C; 16°C; 18°C; and 22°C). k data were showed as ($n.10^{-3}$).

Cultivar	12.5				16				18				22			
	M	k	z	c	M	k	z	c	M	k	z	c	M	k	z	c
'IAC-Carioca-80SH' PP	0	0	0	0	1.1	3	11	0.1	98	17	0.8	1.1	98	21	0.0	6.1
'IAPAR-57'	0	0	0	0	100	11	1.5	6.1	100	20	0.5	9.5	98	24	0.1	9.5
'Vermelho-2157'	12	3	5.5	2.8	100	14	1	6.6	100	18	0.4	6.6	100	20	0.2	6.9
Iratim	95	6	1	3	10	11	1	4.6	100	15	0.5	5.6	100	19	0.0	5.8
'IAC-Carioca-80SH' RC	100	6	2.7	3.8	100	13	1	6.1	98	17	0.5	7.5	100	21	0.0	7.3
'Rosinha-G2'	90	9	2.5	6.3	100	15	0.6	6.3	100	18	0.6	8.6	100	24	0.1	8.7
'Campeão-1'	100	6	3.5	3.9	100	12	1.1	5.9	100	13	0.2	4.1	98	18	0.0	5.4
Guarumbé	92	6	1.3	3.1	100	108	1.1	4.8	98	14	0.5	5.1	100	19	0.1	5.9
'IAC-Carioca-Akytã'	100	7	2.1	3.9	100	14	1	6.8	[illegible]	20	0.2	8.1	100	20	0.1	6.3
'Aporé'	94	6	2.8	3.7	100	14	1	5.8	98	17	0.5	7.1	98	21	0.0	6.1
'Rudá'	100	7	2.1	3.9	100	14	1	8.1	96	19	0.2	7.1	100	28	0.1	9.1

The cultivars responded to temperature in a similar pattern for all these parameters. All synchronization indexes (U) of frequencies' distribution of isothermal germination (Table 3) are positive, indicating that there is a germination times scatter in the temperature treatments (Labouriau and Osborn, 1984). Generally speaking, no significant differences were found amongst U-values from 12.5 to 27°C, showing that germination is evenly scattered in the lines of *Phaseolus vulgaris* tested here.

Table 3. Synchronization indexes of the frequencies' distribution of *Phaseolus vulgaris* isothermal germination. Data in bits ± confidence interval (see Material and methods for details).

Cultivar	temperature (°C)				
	12.5	15.9	18.0	21.9	27.0
'IAC-Carioca-Akytã'	2.26 ± 0.23	0.84 ± 0.36	0.96 ± 0.43	1.32 ± 0.30	1.32 ± 0.45
'Aporé'	1.22 ± 0.43	1.20 ± 0.45	1.41 ± 0.14	1.38 ± 0.54	1.64 ± 0.34
'Campeão-1'	1.87 ± 0.44	1.23 ± 0.51	2.02 ± 0.17	1.62 ± 0.28	1.73 ± 0.41
'IAC-Carioca-80SH' PP	0	0	1.41 ± 0.14	1.38 ± 0.54	1.64 ± 0.34
'IAC-Carioca-80SH' RC	1.43 ± 0.48	1.08 ± 0.36	1.41 ± 0.14	1.44 ± 0.61	1.64 ± 0.34
Guarumbé	2.23 ± 0.52	2.04 ± 0.48	2.19 ± 0.16	1.69 ± 0.44	1.57 ± 0.42
IAPAR-57'	0	1.84 ± 0.35	1.15 ± 0.35	1.15 ± 0.67	1.25 ± 0.31
Iratim	2.27 ± 0.58	1.86 ± 0.36	1.99 ± 0.45	2.17 ± 0.37	1.82 ± 0.19
'Rosinha G2'	1.72 ± 0.17	1.05 ± 0.25	1.06 ± 0.44	1.30 ± 0.19	1.67 ± 0.23
'Rudá'	1.18 ± 0.66	0.82 ± 0.17	0.87 ± 0.45	0.52 ± 0.10	0.53 ± 0.28
'Vermelho-2157'	0.96 ±0.23	0.96 ± 0.23	1.26 ± 0.27	1.16 ± 0.39	0.97 ± 0.27

From cumulative germination curves fitted to Weibull function, the time to germination (GR) of the t_{10} to t_{90} percentiles were calculated for the different temperatures and plotted against temperature (T), as exemplified for cultivars 'IAC Carioca-80SH', both from Rio Claro (Figure 2A and B) and Presidente Prudente (Figure 2C and D). In Figure 2B and 2D, regression lines of GR on T were constrained to a common value of base temperature, calculated as described in M and M.

It was already observed in this paper that linear regressions describe fittingly the relationship between GR and infra-optimal temperatures on the germination of common bean cultivars, as showed by the respective correlation coefficients (Table 4). Usually, Tb values were relatively closed for each percentile although the linear regressions of Tb on percentile (Figure 3) decreased (cultivars 'IAC-Carioca-80SH', 'IAPAR-57', 'Rosinha G2', 'Campeão-1' and 'Aporé'), increased (Iratim, Guarumbé, 'IAC Carioca-Akytã' and 'Rudá') or were statistically (confidence interval, p = 0.05) parallel to the abscissa ('Vermelho 2157'), with exception of the cultivar 'Campeão-1', in which the difference between the highest and the lowest values of Tb was ≅ 2°C, the base temperature varied up to 1.3°C with germination fraction. This range was small enough to allow the assumption that Tb was relatively constant throughout each population of *P. vulgaris* tested here, and that the temperature effect on germination can be described on a thermal-time approach. Similar results were obtained by Garcia-Huidobro *et al.* (1982) with *Pennisetum typhoides*, but Dumur *et al.* (1990) reported that Tb decreased as the percentile value increased in lima bean seeds.

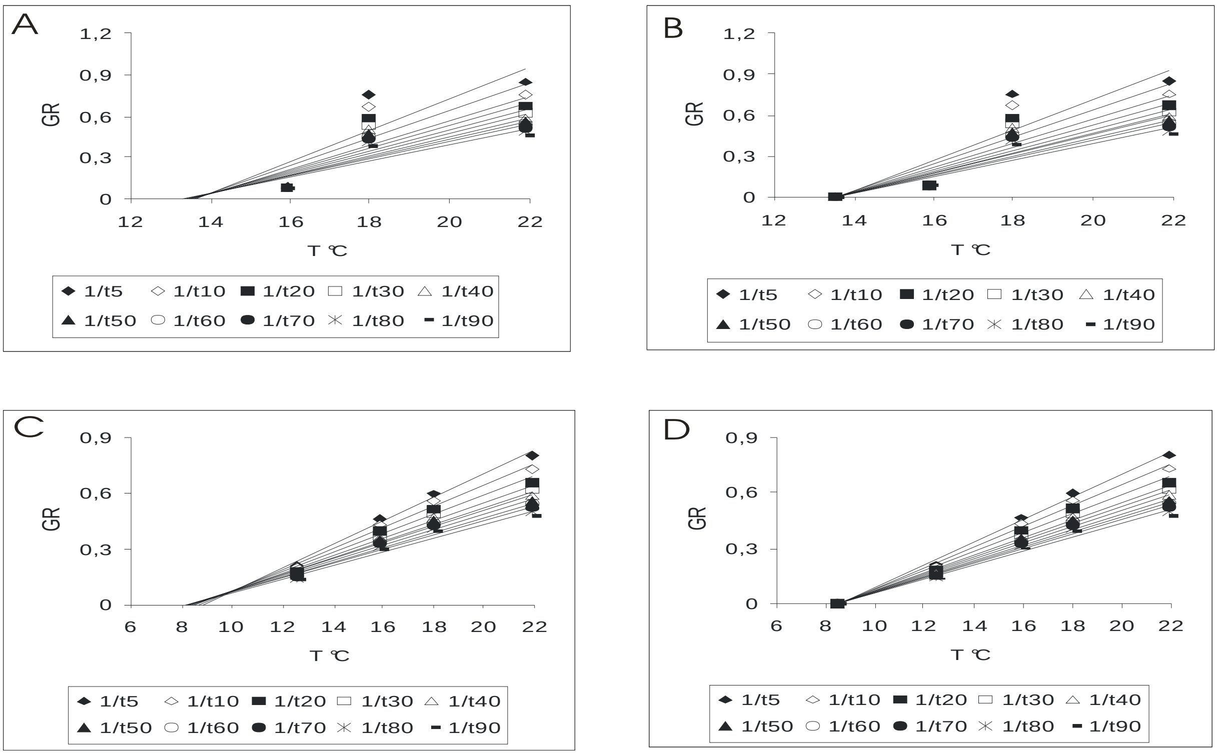

Figure 2. Temperature and rate of germination relations (reciprocal of the germination time of a given percentage, $t_{5\%}$, $t_{10\%}$..., $t_{90\%}$) of *P. vulgaris* cv. 'IAC-Carioca 80SH' from Presidente Prudente (A and B) or from Rio Claro (C and D). The lines are linear regressions not constrained (A and C) or constrained to a common base temperature (B and D) (see M and M for details).

Table 4. Correlation coefficients (R^2) of the linear regression of germination rate ($1/t_{\%}$) on sub-optimal temperatures in different *Phaseolus vulgaris* cultivars. Each rate is the reciprocal of the time (t) to germination of a given fraction (5% to 90%) of the seeds.

Cultivar	Germination rate									
	1/t5	1/t10	1/t20	1/t30	1/t40	1/t50	1/t60	1/t70	1/t80	1/t90
'IAC-Carioca-80SH' PP	0.69	0.71	0.72	0.73	0.74	0.74	0.75	0.76	0.76	0.77
IAPAR-57'	0.95	0.94	0.93	0.93	0.92	0.92	0.91	0.91	0.9	0.89
'Vermelho-2157'	0.92	0.91	0.9	0.9	0.89	0.89	0.88	0.88	0.87	0.87
Iratim	0.96	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.99	0.99
'IAC-Carioca-80SH' RC	0.99	0.99	0.98	0.98	0.97	0.97	0.97	0.96	0.96	0.95
'Rosinha G2'	0.97	0.97	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.99
'Campeão-1'	0.98	0.99	0.99	0.99	0.98	0.97	0.96	0.95	0.94	0.92
Guarumbé	0.97	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
'IAC-Carioca-Akytã'	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
'Aporé'	0.99	0.99	0.99	0.98	0.97	0.97	0.96	0.95	0.95	0.93
'Rudá'	0.94	0.95	0.96	0.97	0.97	0.98	0.98	0.98	0.99	0.99

In the field, a species with low Tb estimates seems more adapted to germinate at cooler temperatures than a species with relatively high Tb (Steinmaus *et al.*, 2000). The different Tb values observed for the two lots of the cultivar Carioca indicate that such a parameter is strongly influenced by the seed provenance: seeds from a warmer place (Presidente Prudente) appeared to be more sensitive to low temperatures than seeds from Rio Claro. These results partially agree with the findings of Otubo *et al.* (1996), according to whom *Phaseolus vulgaris cv.* 'Carioca' is sensitive to low temperature (12°C), since the sensitivity appears to be dependent on the origin of the lot.

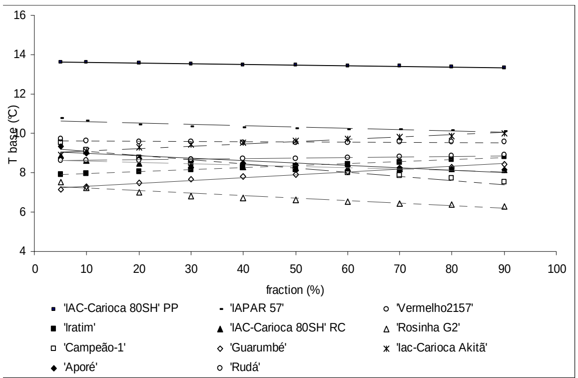

Figure 3. The relation between base temperature and germination fraction (%) of different cultivars of *P. vulgaris*. Each base temperature was estimated as the intercept of the linear regressions of rate of germination on temperature, cf. example in Figure 2. Lines of each cultivar are linear regressions with their correlation coefficients: 'IAC Carioca 80SH' PP (y = -0,003x + 13,62 R^2 = 0,98); 'IAPAR-57' (y = -0,007x + 10,64 R^2 = 0,86); 'Vermelho 2157' (y = -0,001x + 9,63 R^2 = 0,34); Iratim (y = 0,010x + 7,85 R^2 = 0,998); 'IAC Carioca 80SH' RC (y = -0,007x + 8,67 R^2 = 0,80); 'Rosinha G2' (y = -0,013x + 7,34 R^2 = 0,92); 'Campeão-1' (y = -0,021x + 9,30 R^2 = 0,94); Guarumbé (y = 0,014x + 7,18 R^2 = 0,99); 'IAC Carioca-Akytã' (y = 0,012x + 8,99 R^2 = 0,97); 'Aporé' (y = -0,012x + 9,091 R2 = 0,87); and 'Rudá' (y = 0,003x + 8,58 R^2 = 0,96).

When GR (the reciprocal of time taken for a particular fraction to germinate) is linearly related to temperature, whether the base temperature is the same for all seed fractions, the different time-courses of germination at different temperatures, it can be joined in a single curve by plotting germination against thermal time (Gummerson, 1986). Since the plots of the 1/tg against temperature for the different common bean cultivars tested in this work produced acceptably straight lines (Figure 2; Table 4), the thermal time approach was used to analyse them.

A linear relationship between temperature and 50% germination rate was observed in several vegetable species, including *Phaseolus vulgaris* (Bierhuizen and Wagenvoort, 1974), suggesting that it is a common feature in this species. In Figure 4, the mean values of Tb were ordered from lower to higher values, showing that they ranged from ≅ 6.5°C (cultivar 'Rosinha G2') to ≅ 13.5°C ('IAC-Carioca-80SH' PP). However, with exception of these "extreme" values, the base temperatures did not vary so much among different cultivars, ranging around 8.5°C.

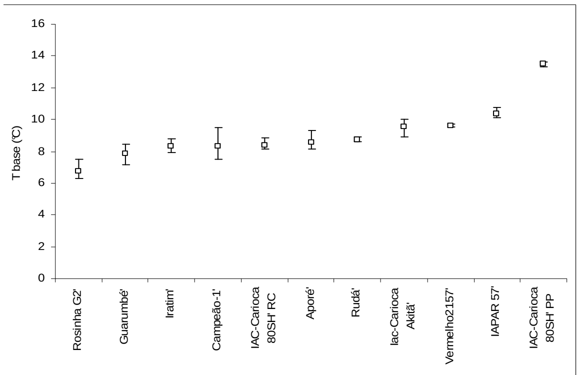

Figure 4. Mean base temperatures (Tb) comparison among different cultivars of *P. vulgaris*. Bars above and below the symbols represent the highest and the lowest Tb values, respectively, estimated for each cultivar.

For all the cultivars, the amount of accumulated thermal time increases with percentile, and the germination progress curves exhibit an apparent sigmoid pattern (Figure 5), similar to the results of Covell *et al.* (1986) for *Cicer arietinum, Lens culinaris, Glycine max* and *Vigna unguiculata*.

In order to compare the rate of increase of thermal time to achieve germination, the relationship between thermal time and percentile was assumed to be linear, and the slope of the regression of thermal time on percentage fraction was taken for each cultivar. The lowest increase rate (lowest slope) was observed for cultivar 'IAC Carioca-Akytã', whereas the highest rate increase occurred for cultivar 'Campeão-1'. The rest of them could be put in decreasing order, as follows: 2) 'Rudá' and 'IAPAR-57'; 3) 'IAC-Carioca 80SH' PP; 4) 'Vermelho 2157'; 5) 'IAC-Carioca 80SH' RC and Guarumbé; and 6) Iratim, 'Aporé' and 'Rosinha G2'. Taking into account that, the lower the slope, the lower the amount of thermal time required for an increment of germination, the rate of progress toward germination per unit of thermal time is higher for the cultivar 'IAC Carioca-Akytã'.

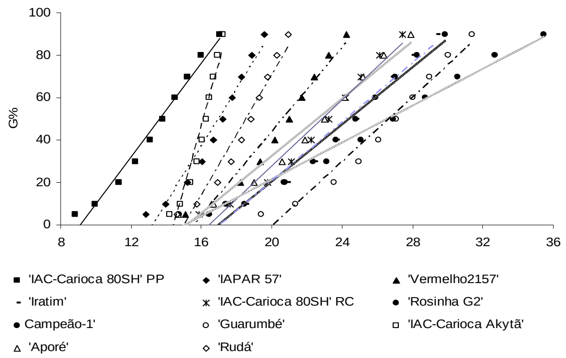

Figure 5. Relation between cumulative germination (G%) and thermal time (°C.day) at several temperatures for different cultivars of *P. vulgaris* and their linear equations and correlation coeficients*:* 'IAC Carioca 80SH' PP (y = 11,06x - 100,44 R^2 = 0,98); 'IAPAR-57' (y = 13,46x - 178,32 R^2 = 0,96); 'Vermelho 2157' (y = 9,86x - 153,75 R^2 = 0,97); Iratim (y = 6,96x - 119,23 R^2 = 0,97); 'IAC Carioca 80SH' RC (y = 7,80x - 128,24 R^2 = 0,97); 'Rosinha G2' (y = 6,77x - 115,27 R^2 = 0,97); 'Campeão-1' (y = 4,39x - 66,67 R^2 = 0,98); Guarumbé (y = 7,55x - 151,41 R^2 = 0,96); 'IAC Carioca-Akytã' (y = 30,26x - 437,43 R^2 = 0,94); 'Aporé' (y = 6,82x - 104,21 R^2 = 0,97); and 'Rudá' (y = 14,30x - 215,37 R^2 = 0,96).

The standardized normal distribution of thermal time values estimated from the regression lines of GR on T are showed for the different cultivars in Figure 6 (solid lines), compared with the actual measured germination percentages plotted on a thermal time scale (symbols), with thermal time = $\theta g = (T - Tb).tg$.

With few exceptions, the points in the Figure 6 show little deviation from a single curve, and one can assume that the base temperature (Tb) was independent of germination fraction (Gummerson, 1986). The fitting of these curves to the observed germination data is reasonable for most of the isotherms, but more variation is apparent for cultivar 'IAC Carioca-Akytã' (Figure 6i). For cultivars 'IAC-Carioca 80SH' PP (Figure 6a) and 'Vermelho 2157' (Figure 6d), the data at 15.9°C and 12.5°C, respectively, deviate from the general relationship, probably due to the relatively low germinability at these temperatures.

Conclusion

High temperatures (≅40°C and upper) strongly inhibit the germination of the cultivars, but 'IAPAR-57', 'Guarumbé', and 'Iratim' appear to be more sensitive to high temperature stress than others. The estimates of base temperatures for seed germination showed few deviations among the cultivars; nevertheless, the cultivars 'IAC Carioca 80SH' PP and 'IAPAR-57' were less tolerant to low temperatures, when compared to others.

The lines exhibit relatively few differences regarding germination rate at the infra-optimum range of temperature, but the response to temperature can be influenced by the provenance of the seed lot, suggesting that estimates of germination response should be derived for locally adapted ecotypes, rather than extended to all members of a species.

The thermal time model could describe, relatively well, the time-course of the cultivars isothermal germination, which differed regarding the amount of thermal time requirement to germination. The cultivar 'IAC Carioca-Akytã' needs fewer degrees per day to achieve germination than others, whereas the cultivar 'Campeão-1' requires more thermal time.

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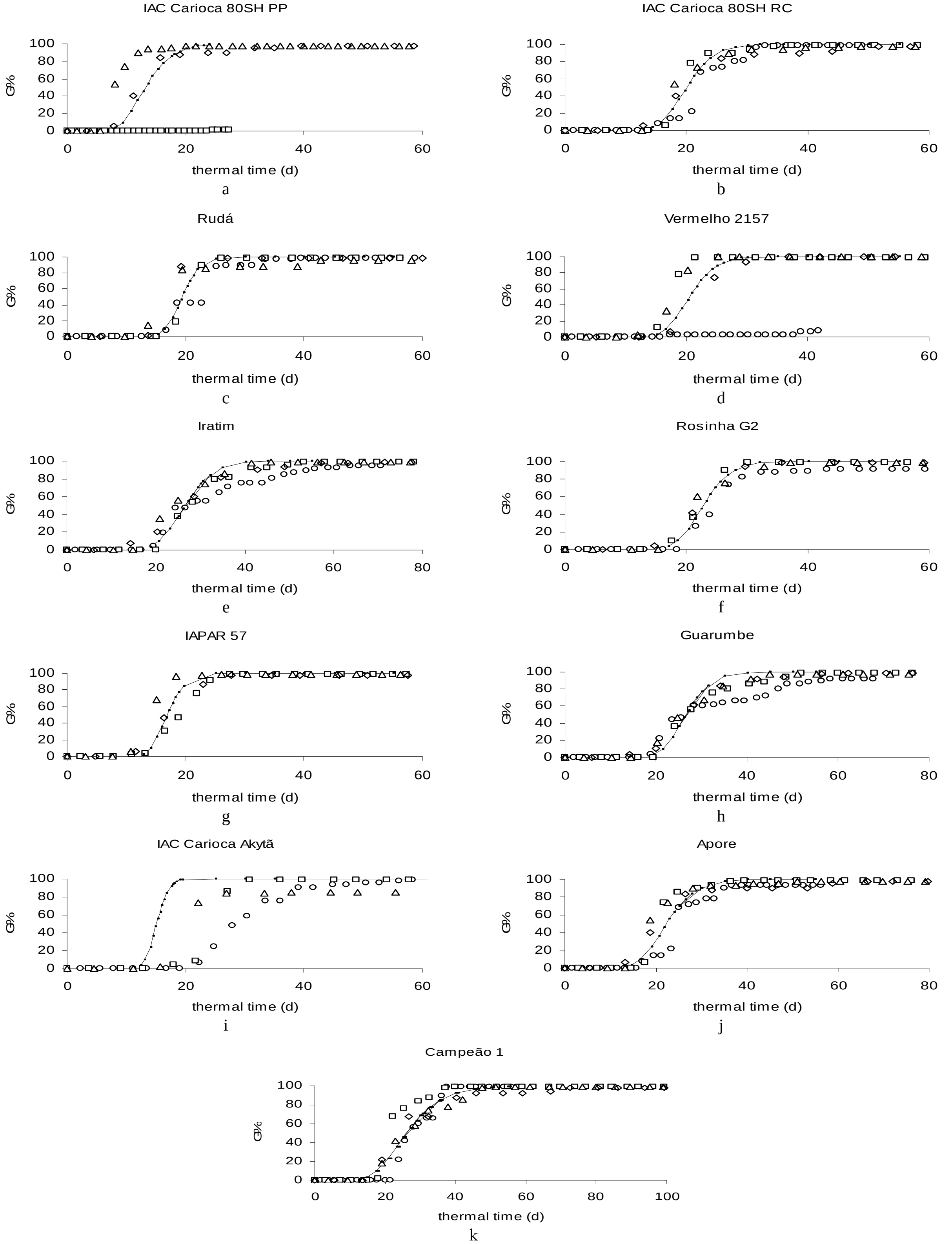

Figure 6. Fitted and observed isothermal germination curves for different cultivars of *P. vulgaris* on a thermal time scale. The fitted lines were $y = 5 + 1/\sigma.(x - \mu)$ with parameters σ and μ: $\sigma = 0.1162$, $\mu = 1,1198$ (A); 0.0777, 1.3019 (B); 0.0684, 1.357 (C); 0.0825, 1.4241 (D); 0.0558, 1.2877 (E); 0.0716, 1.3128 (F); 0.0635, 1.228 (G); 0.0726, 1.4239 (H); 0.0465, 1.1786 (I); 0.0975, 1.3495 (J); 0.1326, 1.4144 (K). Symbols: 12.5°C (O); 16 °C (□); 18°C (Δ); and 22°C (◊).

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