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Seed loss of bean and maize varieties as a function of temperature and irrigation levels

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Abstract. Minimizing seed loss is one of the main goals for a successful crop establishment. The main purpose of this research was to model seed loss of tropically relevant crops, measured both at germination and at emergence, as a function of temperature and irrigation level. Four bean varieties (*catarina, ervilha, manteiga and sondeyombua*) and two maize varieties (*matuba and sam3*) were studied. Experiments were performed in a controlled environment using a thermogradient plate. Temperatures were monitored with Cu-CuNi thermocouples. Seed loss under optimal hydric conditions was simulated at different temperatures, depending on the variety. Eight irrigation levels (6, 7, 8, 9, 10, 12, 15 and 18 mm) were used to simulate the effects of irrigation on losses under optimal thermal conditions. Temperature ranges suitable to the thermal response of each crop were used. A sandy loam-clay textured soil was used in both germination and emergence experiments whereas filter papers in Petri dishes were used for germination experiments only.
Seed loss was minimal along wide thermal or irrigation ranges and increased toward the lowest and highest temperatures and, in most cases, also towards the extreme irrigation levels. The use of even-degree polynomial models successfully identified thermal [T_1, T_2] and irrigation [I_1, I_2] ranges over which losses did not exceed the maximum acceptable losses (*m.a.l.*). The endpoints and length of those ranges were found to be crop-dependent. Differences between estimated polynomial model parameters, for both germination and emergence (L_{min}, T_{min} or I_{min}, and c_t or c_i), highlighted the role of soil in rising the seedling towards the surface. Germination size as a function of temperature also depended on the substrate used.
Both the range lengths and endpoints can be of interest for decision-making regarding crops or varieties to be used or in identifying sowing times for a given crop or variety. Farm weather forecast and warning systems of different nature and agro-climatic zoning may also benefit with the knowledge of these parameters.

1. Introduction

Crop establishment is a major factor for crop productivity. Generalized, fast and uniform emergence is required for a successful crop establishment [1]. A high percentage of seedling emergence (emergence size) increases competitiveness in terms of light, protects against weeds [2, 3] and minimizes soil erosion due to the resulting greater soil cover [4]. On the contrary, germination or emergence losses at sowing time increase the cost of production by decreasing final yields.

Factors such as seed priming [5], field pests [6], pre-sowing tillage [7], mulches [8], soil crusts [9], sowing depth [10], seed size [11], mice [12], oxygen diffusion rate and bulk density [13], among others, can negatively affect the emergence of seedlings, by preventing seed germination and/or hindering the seedlings' rise to the surface. However, soil temperature and soil moisture are the most important and common factors affecting the establishment of crops [14]. Thus, it is important to know the thermal and water requirements of crops, not only to predict the emergence of seedlings [4] but also to compile crop climatic inventories, which are essential input data for the agro-ecological zoning of a given territory [15], or to define agro-climatic zones in a given territory [16, 17]. This knowledge is also essential to choose species or varieties, sowing times, or the depth at which the seeds are placed [18, 19].

Despite the growth of agricultural production in recent years, Sub-Saharan Africa remains the most insecure region in the world in terms of food, with uneven progress in the eradication of hunger [20]. Most of this region is usually classified as Köppen climate types Aw (tropical wet-and-dry), Af (tropical rain forest), BS (semiarid) and Cw (subtropical highland) [21]. Considering the cardinal temperatures estimated for most crops [22], temperature is not the most important limiting factor for crop establishment, at sea level, in this part of the globe. But it may be in the higher altitude areas of the tropics, thus strongly contributing to the bioclimatic zoning of these areas. Soil moisture is usually a serious problem, even in the most humid areas, where high temperatures on the top layers of bare soils, associated with irregular rainfall, lead to quick changes in the soil water content due to high evaporation demand. These conditions are often responsible for heavy losses at sowing [23]. Water economy will always be a central issue to be considered and dealt with in any part of the globe [24].

The not very optimistic prospects for climate evolution in this part of the globe compounds other problems, namely the rate and distribution of income growth and political and economic conditions for agricultural production growth. The latest IPCC (Intergovernmental Panel on Climate Change) report predicts larger increases in temperature in these regions than for others [25]. Furthermore, not only are warmer nights and longer and more frequent heat waves projected for regions between 15° S and 15° N [26], but also a general decrease in rainfall in Africa, associated to the increasing severity and frequency of droughts, negatively affects the prospects for crop productivity [27]. Temperature and precipitation forecasts, to which the IPCC attributes "high confidence", underscore the importance of knowing the thermal [28], and water [29] requirements of crops and their varieties as well as studying measures that mitigate the effects of climate change and adapt crops to the predicted scenarios [30].

There is a vast bibliography addressing the influence of soil temperature and/or moisture either on final germination [31, 32, 33, 34, 35] or on final emergence [4, 36, 37, 38] for different crops. Few studies [39, 40] have addressed the issue in an integrated way, *i.e.,* considering both final germination and emergence in a single study. So far, no reference was found focusing on the relationship between both final emergence and germination due to the abiotic factors mentioned above. From the farmer's point of view, further information is also needed regarding how much rainfall is necessary with dry soil surface in order to minimize sowing losses and how to zone different crops in altitude in order to guarantee sufficiently high emerged seedling percentages.

The main purpose of this research was to model losses at sowing, measured both in terms of germination and emergence, as a function of temperature or of irrigation level, for representative crops of tropical agriculture, in a controlled environment. Specifically, four bean varieties and two maize varieties were studied. The influence of the type of substrate used on the number of non-germinated seeds was also analyzed. Thermal and irrigation ranges over which losses for each variety were minimal, both at germination or at emergence, were also obtained.

2. Material and methods

2.1. Seeds
Seeds of four bean varieties (*Phaseolus vulgaris* L.) and two maize varieties (*Zea mays* L.) were used in the emergence and germination experiments. These are representative crops of tropical agriculture and are the basic "cash crops" for many rural communities**.** Both maize and bean varieties are widely cultivated in Sub-Saharan Africa, and are of great importance from a nutritional, economic, and social point of view. Despite having different characteristics, namely in the levels of rusticity and resistance to pests and diseases, the six varieties chosen have high yield potential.

The bean varieties studied were *catarina, ervilha, manteiga* and *sondeyombua.* The mean weights ± standard deviations of 100 seeds, based on 10 replication samples of 100 seeds of each variety, were 36.6±0.8 g, 34.2±0.9 g, 37.5±0.9 g and 23.6±0.7 g, respectively. The maize varieties considered were *matuba* and *sam3,* and similar weights of 100 seeds were 29.8±1.0 g and 37.0±1.1g, respectively. All seeds used were provided and certified by a relevant ministerial department of Angola, the Estação Experimental Agrícola da Chianga, Huambo. The seeds used in the experiments were selected by visual inspection after immersion for 2 min in a sodium hypochlorite solution (1%) to minimize the risk of bacterial and fungal infection, and were thoroughly washed in distilled water.

Table 1. Examples of measured temperatures, mean (T_{mean}, in ºC) and standard deviations (SD, in °C) resulting from three target ranges of temperatures (9ºC-45°C, 7-40°C, 27-27.5°C) imposed along the thermogradient plate used in experiments performed with *Phaseoulus vulgaris* var. *manteiga* (emergence in soil (E_{soil}) as function of temperature (T) and irrigation (I), and germination with FP method (G_{FP})). Letters A–L stand for the transversal bands of the thermogradient plate. (A) and (L) are the cold and hot ends, respectively.

Experiments	Statistics	Transversal bands													
	(°C)	(A)	A	B	C	D	E	F	G	H	I	J	K	L	(L)
Emergence=f(T)	T_{mean}	9.0	11.8	14.4	16.8	19.1	21.5	24.3	27.5	30.0	32.8	35.5	38.1	40.3	45.2
(E_{soil})	SD	0.5	1.10	1.38	0.49	0.77	0.70	0.98	1.15	1.15	1.27	1.27	1.28	1.54	0.57
Germination=f(T)	T_{mean}	7.1	9.6	12.4	14.7	17.8	19.3	21.6	23.7	26.2	29.0	30.8	34.7	38.5	40.4
(G_{FP})	SD	0.1	0.29	0.23	0.26	0.28	0.23	0.25	0.26	0.28	0.27	0.48	0.52	0.80	0.06
Emergence=f(I)	T_{mean}	27.	25.8	25.7	25.8	25.8	25.5	25.7	25.6	26	26	26.2	26.5	26.9	27.4
(E_{soil})	SD	0.1	0.29	0.39	0.3	0.33	0.36	0.34	0.36	0.32	0.29	0.28	0.2	0.2	0.07

2.2. Thermogradient plate
Emergence and germination experiments were performed on a temperature-controlled thermogradient plate built in the Laboratory of Agrometeorology of Instituto Superior de Agronomia [41], University of Lisbon, Portugal (Lat.: 38º42'N; Long.: 9º10'W; Alt.: 54 m). Uniform thermal gradients along an aluminum alloy plate were achieved by heating the hot end with nine electrical resistances connected in series and by cooling the other end with ethylene glycol pumped from a refrigeration unit. Physical hot and cold ends were 136 cm apart. Different thermal ranges were obtained by changing the energy inputs/outputs on the extremities of the plate. Target basic ranges of temperatures were imposed according to both the known thermal tolerance range of each crop and the substrate used or according to the specific goals of each experiment (Table 1). The substrate temperatures were measured by Type-T thermocouples. Temperatures were monitored every 60 seconds with a CR10 data logger (Campbell Scientific, Inc., Logan, Utah, USA) and hourly averages were recorded. Although the plate was placed in an underground room with small environment temperature variations, the real temperature range varied slightly with the time of year, especially in summertime. Once thermal equilibrium was achieved, the plate's behaviour was stable and the transversal thermal gradients were not significant (Table 1). In order to ensure stability, the plate was left to run for 48 h before beginning each experiment. All experiments were conducted in total darkness.

2.3. Emergence experiments

Twenty-four (24) parallelepiped-shaped aluminum containers (257 mm long, 90 mm wide and 65 mm deep), filled with packed portions of soil, were distributed along the aluminum plate (12 transversal bands × 2 containers per band) (Figure 1a). The portions were collected from the top layer (0-15 cm) of a sandy loam-clay textured soil (Vertisol, according to the World Reference Base for Soil Resource), with a dry bulk density of 1.22±0.02 Mg m^{-3} and an average organic matter content of 2.7±0.17%. The soil water contents at -1,500kPa (wilting point) and at -30kPa (field capacity) were 0.26 cm^3cm^{-3} and 0.42 cm^3 cm^{-3}, respectively. The soil was previously passed through a 2 mm mesh sieve and then dried in an oven at 105ºC for 24 hours. It was previously sterilized to kill any microorganisms or weed seeds that can cause the damping off seedlings [42]. Before each experiment, the initial bulk density was always guaranteed for a volume corresponding to 5.5 cm in depth of each container. Temperatures at sowing depth were measured using twelve thermocouples in direct contact with the soil. For this purpose, one of the containers was chosen in each band.

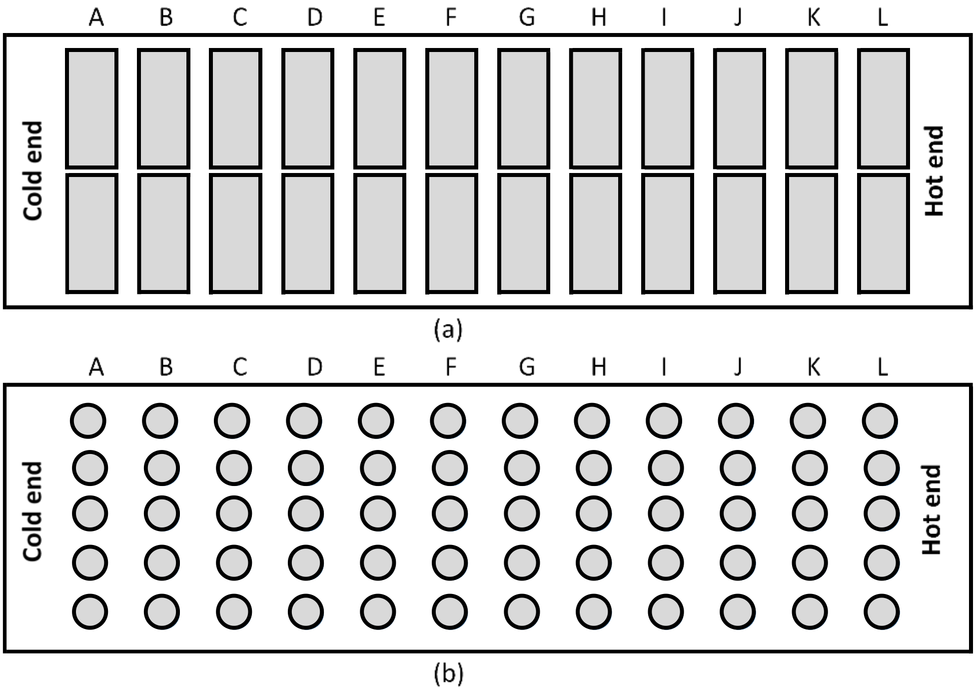

Figure 1. Experimental apparatus (thermogradient plate) in experiments to assess losses at sowing as function of temperature.
Notes: (a) disposition of aluminium containers used in the experiments of emergence and germination with soil (two per band); (b) disposition of Petri dishes used in the experiments of germination with filter paper as substrate (five per band). Letters A–L stand for the transversal bands of the thermogradient plate.

To assess emergence as a function of temperature under adequate moisture content for plant development, the soil was previously moistened and kept at about 90% of the *available capacity* of the soil (equivalent to 513.95 ml applied to each container, *i.e.,* the top 5.24 cm of soil were moistened). Moisture loss due to evaporation from the containers was compensated by adding water daily. Four target ranges of temperature were imposed according the known thermal tolerance range of each variety: 9ºC-50ºC (*catarina*), 9ºC-45ºC (*ervilha* and *manteiga*), 9ºC-42ºC (*matuba*) and 9ºC-40ºC (*sam3* and *sondeyombua*). For all crops, another target range (25ºC-42ºC) was imposed to obtain additional data on the emergence at the highest temperatures, namely in the thermal range in which the final percentage of emerged seedlings tends to decrease.

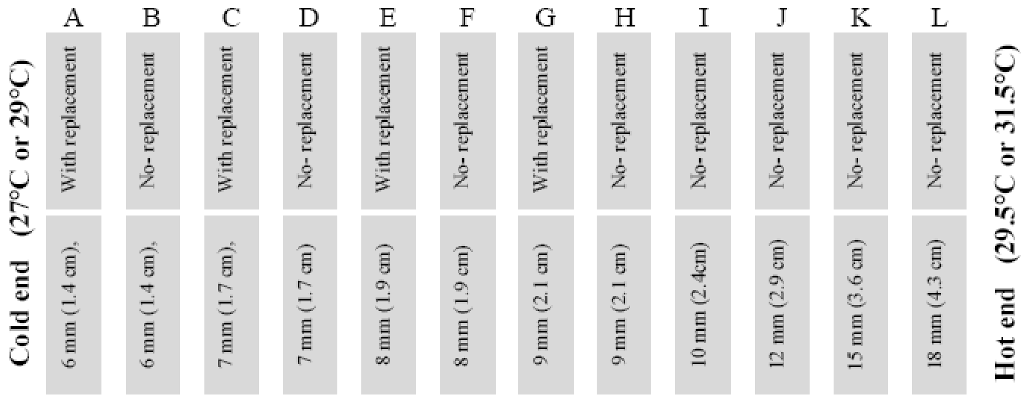

Figure 2. Experimental apparatus (thermogradient plate) in experiments to assess losses at sowing as function of the irrigation level.
Notes: In each box (symbolizing each used container) irrigation levels (from 6 to 18 mm), two experimental conditions (no-replacement or replacement of water every two days) and moistened depth in each band are shown (from 1.4 to 4.3 cm). Letters A–L stand for the transversal bands of the thermogradient plate.

When emergence was evaluated as a function of soil moisture under optimal thermal conditions to achieve high final emergences, the soil was moistened with amounts of water equivalent to 8 different irrigation levels, namely 6, 7, 8, 9, 10, 12, 15 and 18 mm (Table 2). Identical amounts replenished the soil every two days for the first four cases (6, 7, 8 and 9 mm with replacement), making a total of twelve different soil water conditions (Figure 2). Two target basic ranges of temperature were imposed: 27ºC-27.5ºC for bean varieties and 29ºC-29.5ºC for maize varieties. Both ranges are associated with temperatures that guaranteed minimal losses in the temperature experiment.

Table 2. Moistened soil thickness as a function of the irrigation level applied (in ml and mm).

Irrigation amount		moistened soil depth
(mm)	**(ml)**	**(cm)**
6	138.8	1.4
7	161.9	1.7
8	185.4	1.9
9	208.2	2.4
10	231.3	2.4
12	277.6	2.9
15	347.0	3.6
18	416.3	4.3

In all instances, ten seeds per container were placed at 2 cm depth about 2.5 cm apart, totaling 20 seeds for each temperature/band or watering/band. The frequency of emerged seedlings was initially counted every 4 h, then every 6 h and finally at every 8 h, as the experiment progressed. Seedlings were considered emerged when cotyledons (bean varieties) or terminal buds (maize varieties) were visible at soil surface. Each experience ended when emergence ceased in all bands for 48 consecutive hours. In most cases, emergence was found at both ends of the experimental thermal ranges. Emergence in soil will be denoted as E_{soil}, for both temperature and irrigation level experiments.

2.4. Germination experiments

Sixty (60) glass Petri dishes**,** with 90 mm internal diameter (12 transversal bands × 5 dishes per band) were distributed along the plate (Figure 1b). One target basic range of temperatures was imposed: 7ºC-40ºC for all the varieties in study. For all crops, another target range (25ºC-42ºC) was imposed to obtain additional data on the germination at the highest temperatures, namely in the thermal range where the final percentage of germinated seeds tends to decrease. The seeds were placed on the thermogradient plate inside the covered Petri dishes, on filter papers (Wathman 40) which were kept permanently wet with at least 1 mm of distilled water (Filter Paper method, G_{FP}). Twelve thermocouples (in direct contact with the moistened filter paper) were used to measure temperatures inside the dishes. For this purpose, a Petri dish was chosen at random in each band.

Twenty seeds were placed in each dish, totaling 100 seeds for each temperature/band. Seeds were considered germinated when the protrusion of the radicle was at least 2.0 mm [28, 32, 43, 44]. Germinated seeds were counted and then removed from the dishes. Counting frequency of germinated seeds was like that for the emerged seedlings. Petri dishes along each transversal band were re-randomized after each count. Each experiment ended when germination had ceased in all bands, for 48 consecutive hours. In most cases, germination was found at both ends of the experimental thermal ranges.

At the end of emergence experiments, the number of seeds that had germinated, but not emerged, was also counted in each container, using the same criteria described above. This additional count made it possible to add a new parameter to the study: the "percentage germination in the soil", either as a function of temperature (non-limiting soil water conditions) or of irrigation level (non-limiting thermal conditions). Germination in soil will be denoted as G_{soil}, both when studying losses at sowing as a function of temperature or of irrigation level.

Total emergence and total germination at each temperature or irrigation level were measured as percentage of the seeds sown and considered the final emergence (E_f) or germination (G_f), respectively.

2.5. *Analytical procedures*

In this study, both seedlings that did not emerge, (100-E_f) %, or non-germinated seeds, (100-G_f) %, were considered losses at sowing. Tolerable losses at sowing (which vary with location) are usually recommended in agronomical practices. According to the FAO Quality Declared Seed (QDS) [45], the percentage of seeds that can germinate and develop must be at least 80% for maize and 70% for beans. These values were used in this work to define the admissible maximum values for losses at sowing, hereafter called the *maximum acceptable loss* (*m.a.l.*), which were therefore 20% for maize and 30% for beans.

In order to choose the most suitable model for seed loss at germination (on two substrates) and emergence due to temperature or irrigation, several issues were considered such as the prediction accuracy and efficiency, the available sample sizes, the number of model parameters that are to be estimated and statistical and computational issues, as well as the applicability of each model to a wide range of crops and their varieties. Good model fits are a necessary, but not sufficient requirement. The results must be useful in practice. The observed underlying relationship determined the option taken.

The R statistical software [46] was used to fit the models for losses at sowing. The statistical significance of differences between the estimates of each parameter for different varieties were assessed based on whether their respective 95% confidence intervals intersected. The standard linear regression coefficient of determination,

$$R^2 = 1 - \frac{RSS}{TSS} \quad (1)$$

where RSS is the residual sum of squares and TSS the total sum of squares does not have all the familiar properties in a non-linear regression and need not fall in the interval [0,1]. However, RSS/TSS is a sensible and dimensionless measure of goodness-of-fit, for which near-zero values indicate good fits.

3. Results

3.1. Losses at sowing as a function of temperature (E_{soil} vs. G_{soil})

For all crops, a U-shaped pattern was observed in the relationship between losses at sowing (either at emergence or at germination) and temperature. This suggests that the losses were minimal along a broad thermal range and only increased noticeably toward the most extreme temperatures considered (Figure 3). For temperatures close to 11-12ºC and above 37-38ºC there was often no emergence, although losses at emergence were not total at the hottest end for *sam3* and *sondeyombua* varieties and at both ends for *matuba*. Along the intermediate thermal range, the losses were low and often close to zero for *catarina*, *ervilha* and *manteiga*. Losses at germination were generally lower than those recorded at emergence, *i.e.* not all germinating seeds emerge. The proportion of seeds germinated but not emerged (G_f-E_f) was highest for the most extreme temperatures and was more noticeable for the varieties *catarina* (at both ends), *manteiga* and *sonde* (mainly in the coldest end). The differences for *matuba* were visible only at higher temperatures whereas for *ervilha* they were only noticeable at two temperatures (14.1 ºC and 35.2 ºC). Sometimes, the differences were highest at the second lowest (*manteiga*, *sam3*) or second highest (*catarina*, *ervilha*, *manteiga*, *sam3*) temperature studied, rather than at the most extreme temperatures.

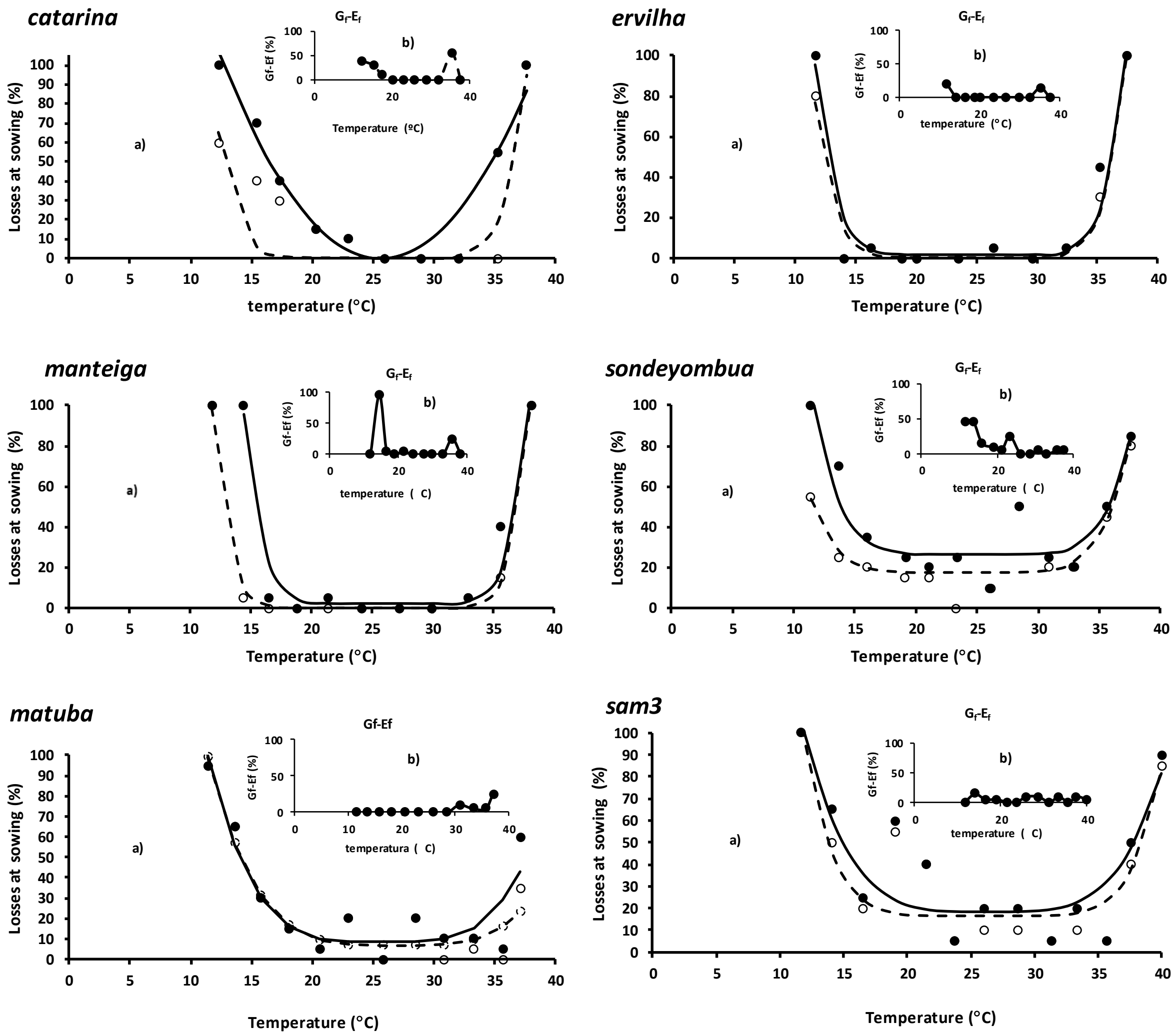

Figure 3. Losses at sowing as a function of temperature.

Notes: a) Relationships between losses at sowing (100-G_f or 100-E_f, in %) and temperature (in mm) for four bean varieties (*catarina*, *ervilha*, *manteiga* and *sondeyombua*) and two maize varieties (*matuba* and *sam3*) sowed in aluminium containers filled with soil (E_{soil} and G_{soil}), fitted by a polynomial model (Eq. 2): • observed 100-E_f; o observed 100-G_f; —— estimated 100-E_f; - - - - estimated 100-G_f. b) (at the top of the larger graph area). Relationships between observed G_f-E_f (in %) and temperature (in ºC), for the same substrate and varieties.

Based on this observed U-shaped pattern, an even-degree polynomial function $f_k(T)$ was fitted to describe the relationship between (100-E_f)% or (100-G_f)% (losses at emergence or at germination, respectively) and temperature (T, in ºC):

$$f_k(T) = L_{min} + \left(\frac{T - T_{min}}{c_t}\right)^{2k} \qquad (\%) \qquad (2)$$

The positive integer parameter k (={1,2,3,…}) controls the shape of the flattened basin with losses close to the function minimum, L_{min}, that is, close to the minimum value of non-emerged or non-germinated seeds (in %). The function is symmetric around T_{min}, the temperature (in ºC) at which L_{min} was attained. The parameter c_t (in ºC) is also associated with the basin width.

This model was fitted for small, fixed values of k and, for each k considered, estimates of L_{min}, T_{min} and c_t were obtained using standard non-linear regression procedures. The solution selected was the one which, among the values of k considered, minimized the Residual Sum of Squares (RSS) and Akaike's Information Criterion (AIC). Whenever estimated values of L_{min} were negative (a physical impossibility), the model was again fitted forcing L_{min}=0 in Eq. (2), thereby estimating only two parameters, T_{min} and c_t. By setting, in this equation, $f_k(T)$ = *m.a.l.* for each crop, it was possible to estimate both lower (T_1) and upper (T_2) limits of thermal ranges which guarantee losses below the maximum acceptable loss.

The results are shown in Table 3. Goodness-of-fit measures (RSS, RSS/TSS and AIC) were generally good for all varieties, mainly for *ervilha* and *manteiga*. The best fits for emergence losses were obtained with polynomials of degree 2k smaller than or equal to those that optimized the fits for germination losses, being the differences clearly greater for *catarina* when compared with the others. For emergence they were obtained with k=1 for *catarina*, k=2 for *sam3*, *sondeyombua* and *matuba* and k=4 for *ervilha* and *manteiga*. For germination they were obtained with k=2 for *matuba*, k=3 for *sam3* and *sondeyombua*, k=4 for *ervilha and catarina*, and k=5 for *manteiga*. For four varieties, the c_t values (parameter associated with the width of the basin) obtained for the emergence were significantly different from those found for germination (only in the cases of *ervilha* and *matuba* were there overlap of the 95% confidence intervals). The differences found between both the c_t and 2k values were greater for the *catarina* than for any other case.

Values of L_{min}, and T_{min} also depended on the variety considered. Among bean varieties, values of L_{min} for *sondeyombua* were considerably larger (23.1% and 17.6% for emergence and germination, respectively) than those of other varieties (which were often zero or near-zero). Among maize varieties, *sam3* presented larger values of L_{min} than *matuba* (18.6% and 8.5% for emergence and 16.6% and 6.8% for germination, respectively).

For the different varieties, minimal losses at emergence were obtained at relatively similar temperatures T_{min}, which ranged from 24.5ºC (*ervilha*) to 26.2ºC (*manteiga*) among bean varieties. Minimal losses for *matuba* and *sam3* were obtained at 25.8ºC and 26.4ºC, respectively. Relevant differences between T_{min} values were only found between *ervilha* and four of the remaining varieties (*catarina*, *manteiga* and the two maize varieties) and between *manteiga* and *sondeyoumbua*. Minimum germination losses were recorded at temperatures T_{min} ranging from 23.9ºC (*sondeyombua*) to 24.7ºC (*catarina*) among bean varieties, and of 26.2ºC for *sam3* and 27.0ºC for *matuba*. Relevant differences were only found between bean varieties, on the one hand, and maize varieties, on the other. Although T_{min} for emergence was generally lower than for germination (with the sole exception of *matuba*), these estimated differences were statistically relevant only for *manteiga* (whose 95% confidence intervals did not overlap those of other crops).

By cutting off the graph of each even-degree polynomial function (Eq.2) with horizontal lines representing *m.a.l.* (20% for maize varieties and 30% for beans) two temperatures (T_1 and T_2) are obtained, defining a crop-dependent thermal interval [T_1, T_2] along which losses, either at emergence or at germination, were smaller than *m.a.l.* For E_{soil}, *ervilha* had the smallest T_1 (the lower interval endpoint) for emergence (13.5ºC) and *catarina* the largest (18.5ºC). Among maize varieties, *sam3* requires a considerably higher minimum temperature for an acceptable emergence size (21.1ºC) than *matuba* (17.2ºC). The upper endpoint, T_2, for beans ranged from about 32-33ºC (*catarina* and *sondeyombua*) to about 36ºC (*ervilha* and *manteiga*) whereas *matuba* had a greater T_2 (34.4ºC) than *sam 3* (31.7ºC).

The values of T_1 for G_{soil} were generally lower than those for E_{soil} (*matuba* being the exception), while T_2 values for G_{soil} were greater than or equal to the values for E_{soil}. Differences between the T_1 values reached about 5ºC for *catarina*, while those between the T_2 values reached about 3ºC for *catarina* and *sam3*. Thus, basins for germination were always wider than those for emergence (differences ranged from 0.4ºC for *ervilha* to more than 6ºC for *catarina*, *sondeyombua* and *sam3*). For the *m.a.l.* considered (Table 3) *ervilha* and *manteiga* presented the longest basins among bean varieties (greater than 20ºC for both E_{soil} and G_{soil}). The troughs estimated for *catarina* and *sondeyoumbua* were about 14-15ºC for emergence and 21-22ºC for germination. Among maize varieties, *sam3* had a narrower basin than *matuba*.

Table 3. Losses at sowing as a function of temperature. Parameters estimated from the even-degree polynomial model used (Eq. 2) to simulate losses either at germination or at emergence (expressed as % non-emerged seedlings and non-germinated seeds, respectively), for bean (*catarina*, *ervilha*, *manteiga* and *sondeyoumbua*) and maize (*matuba* and *sam3*) varieties.

Crop variety	Exp.	*m.a.l.*	k	L_{min}	conf. int. (95%)	T_{min}	conf. int. (95%)	c_t	conf. int. (95%)	T_1	T_2	RSS	RSS/TSS	AIC
		(%)		(%)		(°C)			(°C)	(°C)				
catarina	E_{soil}	30	1	0	-	25.6	[24.92, 26.32]	1,3	[1.20, 1.37]	18.5	32.7	972.9	0.07	80.2
	G_{soil}		4	0	-	24.7	[24.13, 25.18]	7.3	[7.02, 7.63]	13.6	35.6	2779	0.28	90.5
	G_{TP}		1	12.5	[2.00, 23.08]	22.6	[21.70, 24.03]	1.8	[1.50, 2.10]	15.1	30.1	1694	0.19	108.2
ervilha	E_{soil}	30	4	1.6	[-5.74, 9.02]	24.5	[24.28, 24.75]	7.3	[7.11, 7.42]	13.5	35.6	920.4	0.06	87.9
	G_{soil}		4	0.7	[-3.71, 5.05]	24.4	[24.21, 24.53]	7.4	[7.26, 7.48]	13.1	35.6	324.4	0.03	76.4
	G_{TP}		1	13.0	[5.62, 20.36]	23.0	[22.17, 23.78]	1.6	[1.48, 1.79]	16.3	29.7	1018	0.09	107.7
manteiga	E_{soil}	30	4	2.1	[-5.96, 10.17]	26.2	[25.96, 26.41]	6.7	[6.83, 6.83]	16.1	36.3	855.5	0.06	80.9
	G_{soil}		5	0.7	[-0.33, 1.77]	24.3	[23.86, 24.77]	8.7	[8.41, 8.99]	12.1	36.5	16.4	0.002	41.4
	G_{TP}		1	19.9	[14.32, 23.52]	22.6	[22.00, 23.26]	1.8	[1.66, 1.92]	16.7	28,6	293.2	0.05	80.4
sonde yombua	E_{soil}	30	2	23.1	[14.95, 31.27]	25.0	[24.38, 25.68]	4.6	[4.25, 4.85]	17.7	32.4	1157	0.13	98.7
	G_{soil}		3	17.6	[9.02, 26.20]	23.9	[23.08, 24.70]	6.9	[6.37, 7.36]	13.4	34.3	1455	0.25	99.6
	G_{TP}		1	13.6	[6.86, 20.28]	23.9	[23.28, 24.57]	1.5	[1.42, 1.66]	17.7	30.2	605.5	0.05	89.1
matuba	E_{soil}	20	2	8.5	[-0.39, 17.48]	25.8	[24.94, 26.80]	4.7	[4.24, 5.08]	17.2	34.4	1353	0.14	98.8
	G_{soil}		2	6.8	[-0.42, 14.07]	27.0	[25.40, 28.56]	5.0	[4.41, 5.64]	17.4	36.6	947.7	0.10	94.5
	G_{TP}		2	6.9	[2.44, 11.36]	23.9	[23.44, 24.28]	5.0	[4.83, 5.19]	14.3	33.4	382.2	0.04	83.6
Sam3	E_{soil}	20	2	18.6	[6.41, 30.75]	26.4	[25.38, 27.40]	4.8	[4.37, 5.28]	21.1	31.7	3130	0.25	116.2
	G_{soil}		3	16.6	[5.91, 27.3]	26.2	[25.48, 26.84]	6.9	[6.49, 7.28]	17.7	34.6	2757	0.23	114.5
	G_{TP}		2	5.6	[-0.29, 11.57]	24.6	[24.08, 25.19]	5.3	[5.07, 5.55]	14.3	35.0	761.7	0.07	97.8

Notes: Exp. – Experiments; E_{soil} – emergence experiment performed in soil; G_{soil} – germination experiment performed in soil; G_{TP} – germination experiment performed on filter paper; *m.a.l.* – maximum acceptable losses; k (shape parameter); estimates of L_{min} (minimal loss), T_{min} (the central point of the basin) and c_t (extent of the basin), and corresponding 95% confidence intervals; T_1 and T_2 – lower and upper thermal limits, respectively of the range along which losses were less than *m.a.l.*; RSS, RSS/TSS and AIC - corresponding measures of "goodness-of-fit".

3.2. Losses at germination (G_{soil} vs. G_{TP})

When accounting for seed loss at germination as a function of temperature along a relatively wide thermal range, the results revealed that losses were not the same for the different substrates considered, sandy loam-clay soil and filter paper soaked in water (Figure 4). Although in both cases Eq. (2) fits the observed data well, neither the exponent 2k in the best fit, nor the values of L_{im}, T_o and c were, in most cases, similar. Despite a relatively small number of degrees of freedom, the differences are often statistically relevant (based on the overlaps of their respective 95% confidence intervals).

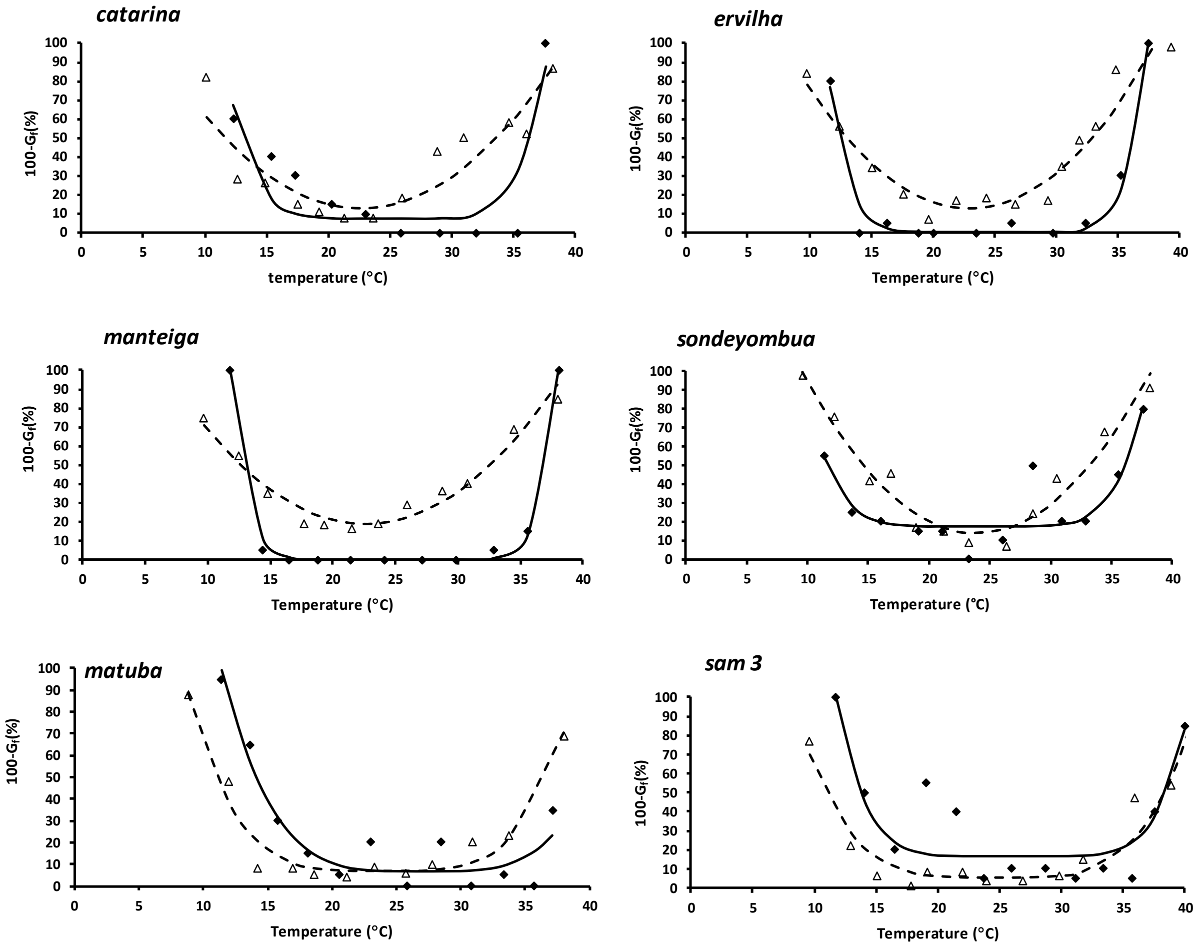

Figure 4. Losses at germination as a function of the substrate used.
Notes: Relationships between losses at germination (100-G_f, in %) and temperature (in °C), fitted by a polynomial model (Eq. 2) for four bean varieties (*catarina*, *ervilha*, *manteiga* and *sondeyombua*) and two maize varieties (*matuba* and *sam3*) and using two different substrates (soil and filter paper): ♦ observed 100-G_f in soil; Δ observed 100-G_f on filter paper; —— estimated 100-G_f in soil; --- estimated 100-G_f on filter paper.

Best simulations for losses at germination, G_{TP} (Table 3), were obtained with k=1 for bean varieties and k=2 for maize varieties, values that were lower than those for G_{soil} in five cases (only *matuba* had similar k values). Values of c_t for bean varieties were significantly greater for G_{soil} when compared to those obtained for G_{TP} (non-overlapping 95% confidence intervals), but were similar for maize varieties. Not surprisingly, when soil is used as the substrate the thermal ranges ensuring minimal losses, T_2-T_1, were longer for beans than for maize (Figure 4). For a given value of *m.a.l.*, the length of the ranges also depends on L_{min}. Whenever the L_{min} values for G_{TP} were significantly larger than for G_{soil}, the thermal interval length T_2-T_1 was clearly longer for germinations occurring in the soil, rather than on filter paper (ranging from about 7ºC for *catarina* to 12.5ºC for *manteiga*). When G_{soil} and G_{FP} had similar values for L_{min} (the case of *matuba*), T_2-T_1 was similar in both substrates. Finally, when the estimated value of L_{min} for G_{TP} was greater than for G_{soil}, [T_1, T_2] was wider for the germination on filter paper in the case of *sam3* (at about 4ºC for differences of c_t about 1.5ºC) but narrower in the case of *sondeyombua* (at about 8.4ºC for differences of c_t about 5.5ºC). Despite the sometimes-considerable differences between L_{min} estimated by G_{soil} and G_{FP}, only for *ervilha* and *manteiga* were they statistically relevant. Except for *sondeyombua*, values of T_{min} were lower in G_{soil} than in G_{TP}. These differences ranged from 1.4ºC (*ervilha*) to 3.1ºC (*matuba*).

3.3. Losses at sowing as a function of irrigation levels (E_{soil} vs. G_{soil})

When plotting losses at sowing (100-E_f or 100-G_f, both in %) *versus* irrigation levels (eight without water replacement, from 6 mm to 18 mm), the trend of the observed data series suggests that the losses were nearly minimal along a fairly broad range, increasing toward both extreme levels considered in the case of *catarina*, *ervilha* and *sondeyoumbua* or only toward the lowest irrigation levels for *manteiga*, *matuba* and *sam3* (Figure 5). When the soil was initially watered with 138.8 ml (equivalent to 6 mm), losses at emergence were maximum for *catarina*, *ervilha*, *matuba* and *sam3*, 85% for *manteiga* and 80% for *sondeyombua*. For *catarina* and *ervilha* varieties, they were also relevant (85% and 90%, respectively) when the initial watering was 18 mm. Losses at germination were generally lower than those recorded at emergence. The proportion of seeds germinated but not emerged (G_f-E_f) was mainly visible for the smallest irrigation amounts, and were often greater than 25%. G_f-E_f was also relevant for *ervilha* when 18 mm was initially applied. For most varieties (*manteiga* was the exception) G_f-E_f values were greater for 7 mm than for 6 mm and nearly minimal for intermediate irrigation levels.

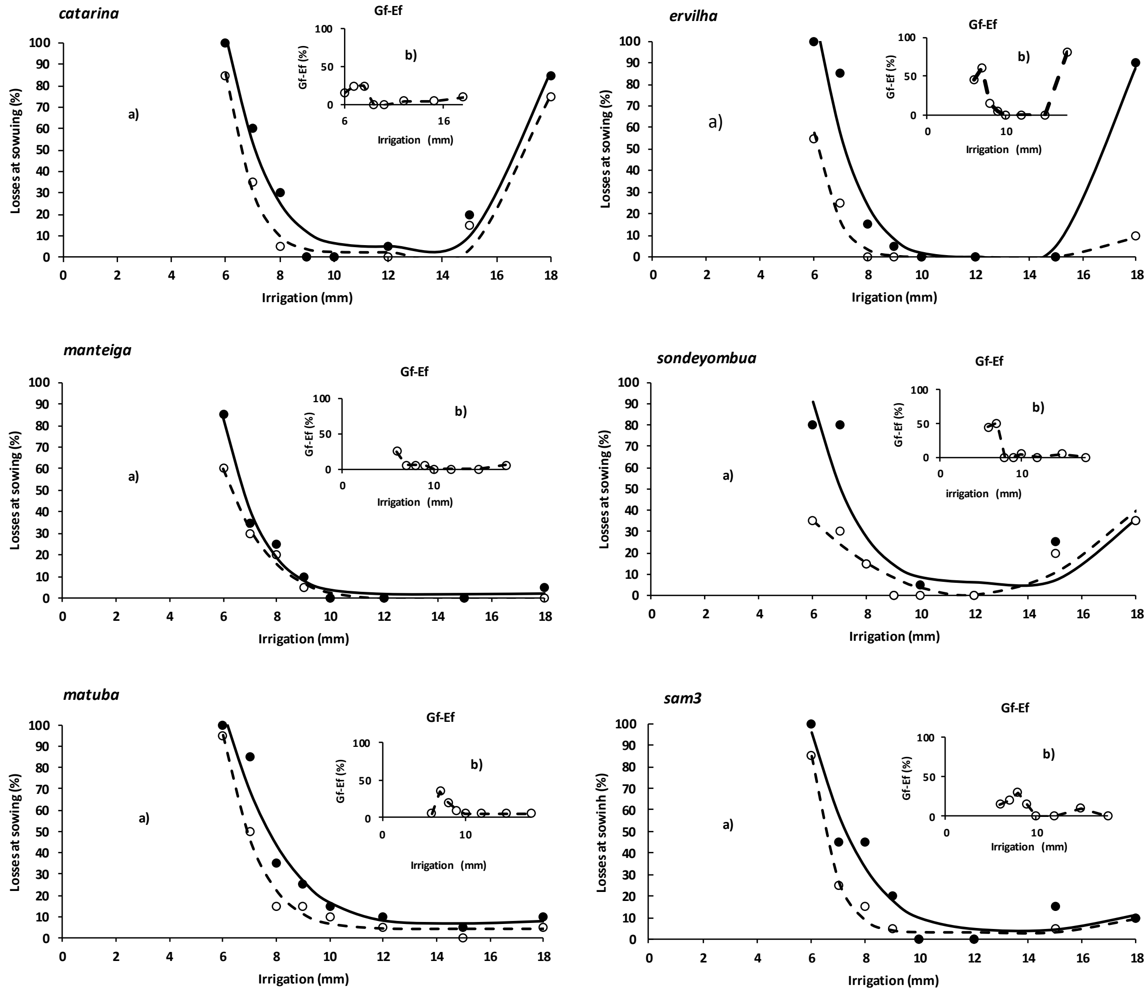

Figure 5. Losses at sowing as a function of irrigation level.

Notes: a) Relationships between losses at sowing (100-G_f or 100-E_f, in %) and irrigation (in mm) for four bean varieties (*catarina*, *ervilha*, *manteiga* and *sondeyombua*) and two maize varieties (*matuba* and *sam3*) sowed in aluminium containers filled with soil (E_{soil} and G_{soil}), fitted by a polynomial model (Eq. 3): • observed 100-E_f; o observed 100-G_f; —— estimated 100-E_f; - - - - estimated 100-G_f. b) (at the top of the larger graph area) Relationships between observed G_f-E_f (in %) and irrigation (in mm), for the same varieties and substrate.

The U-shaped pattern found for the relationship between losses at emergence or at germination and irrigation levels suggested using an equation similar to Eq. (2):

$$f_k(I) = L_{min} + \left(\frac{I - I_{min}}{c_i}\right)^{2k} \quad (\%) \qquad (3)$$

where I denotes the irrigation level, I_{min}, the irrigation level at which a minimum loss (L_{min}) is registered, and c_i is a parameter associated with the basin width. I, I_{min}, L_{min}, and c_i were expressed in mm. Parameter k has the same meaning as in Eq. (2). The fitting procedures were the same as those used above. Negative values for L_{min} were found in the case of *ervilha*, and new fits were made for both E_{soil} and G_{soil} taking L_{min}=0. The estimates of the lower (I_1) and the upper (I_2) endpoints of irrigation ranges which guarantee losses below certain tolerance levels were obtained by taking f_k (I) = *m.a.l.* for each crop.

Not surprisingly, losses at sowing as a function of the irrigation amount were also well-described by even-degree polynomials (Figure 5). However, the best fits did not always guarantee values of I_{min} below 18 mm, which was the upper limit of the irrigation levels tested. Such were the cases of *manteiga* and *matuba* varieties, for which the level of fit improved, albeit very slightly, as ever larger exponents (2k) were considered. In these cases, the solution chosen was the best fitting value of k that guaranteed I_{min} values between 6 and 18 mm.

Table 4. Losses at sowing as a function of irrigation levels. Parameters estimated from the even-degree polynomial model used (Eq. 3) to simulate losses either at germination or at emergence (expressed as % non-emerged seedlings and non-germinated seeds, respectively), for bean (*catarina*, *ervilha*, *manteiga* and *sondeyoumbua*) and maize (*matuba* and *sam3*) varieties.

Crop variety	Exp.	*m.a.l.*	k	L_{min}	conf. int. (95%)	I_{min}	conf. int. (95%)	C_i	conf. int. (95%)	I_1	I_2	RSS	RSS/TSS	AIC
		(%)		(%)		(mm)			(mm)	(mm)				
catarina	E_{soil}	30	2	4.9	[-3.08, 12.92]	12.1	[11.96, 11.33]	2.0	[1.87, 2.03]	7.8	16.5	366.5	0.03	61.3
	G_{soil}		3	2.6	[-2.94, 8.14]	12.1	[11.96, 12.18]	2.9	[2.84, 2.97]	7.0	17.1	203.3	0.02	45.4
ervilha	E_{soil}	30	2	0	-	12.2	[11.92, 12.45]	1.9	[1.81, 1.98]	7.7	16.6	1135	0.06	68.3
	G_{soil}		3	0	-	12.8	[12.53, 13.13]	3.5	[3.34, 3.66]	6.7	19.0	56.8	0.02	46.4
manteiga	E_{soil}	30	3	1.7	[-2.92, 6.25]	14.6	[12.58, 16.71]	4.1	[3.14, 5.15]	6.7	19.0	109.9	0.02	51.7
	G_{soil}		3	0.7	[-3.44, 2.14]	16.2	[14.35, 18.07]	5.2	[4.21, 6.10]	7.1	25.3	32.5	0.01	41.9
sonde youmbua	E_{soil}	30	2	6.0	[-11.11, 23.05]	12.8	[11.88, 13.68]	2.2	[1.85, 2.61]	7.8	17.7	1687	0.22	73.5
	G_{soil}		1	0,0	[-7.72, 7.66]	11.8	[11.22, 12.39]	1.0	[0.81, 1.15]	6.4	17.2	226.2	0.13	57.4
matuba	E_{soil}	20	2	6.8	[-2.35, 15.90]	15.1	[12.36, 17.79]	2.9	[1.99, 3.76]	9.6	20.6	380.2	0.04	61.6
	G_{soil}		4	4.2	[-0.60, 9.06]	16.9	[14.34, 19.48]	6.2	[4.74, 7.67]	8.2	25.7	112.3	0.01	51.7
sam3	E_{soil}	20	2	4.5	[-5.01, 14.00]	13.9	[12.23, 15.53]	2.5	[1.96, 3.13]	8.8	18.9	559.7	0.07	64.7
	G_{soil}		4	3.4	[0.41, 6.45]	13.0	[12.54, 13.38]	4.0	[3.76, 4.27]	7.3	18.7	69.0	0.01	47.9

Notes: Exp. – experiments; E_{soil} – emergence experiment performed in soil; G_{soil} – germination experiment performed in soil; *m.a.l.* – maximum acceptable losses; k (shape parameter); estimates of L_{min} (minimal loss), I_{min} (the central point of the basin) and c_i (extent of the basin) and corresponding 95% confidence intervals; I_1 and I_2 – lower and upper thermal limits, respectively, of the range along which losses were less than *m.a.l.*; RSS, RSS/TSS and AIC - corresponding measures of "goodness-of-fit".

Results are shown in Table 4. Goodness-of-fit measures (RSS, RSS/TSS and AIC) were generally good for all varieties. The best solutions chosen for (100-E_f)% were obtained with k=3 for *manteiga* and k=2 for the remaining varieties, whereas those for (100-G_f)% were obtained with k=3 for *catarina*, *ervilha* and *manteiga*, k=4 for *matuba* and *sam3* and k=1 for *sondeyoumbua* (the only case where k for losses at germination was less than that found for losses at emergence). Values of c_i for G_{soil} were generally larger than for E_{soil} (*sondeyoumbua* was the exception). Only for *manteiga* these differences were not significant. Therefore, the irrigation ranges associated with acceptable losses, [I_1, I_2], were longer for G_{soil} than for E_{soil} (even for *sondeyombua*). This means that the moisture levels in the topsoil that allow a seed to germinate may not be sufficient to guarantee the emergence of the resulting seedling.

Matuba had the greatest L_{min} values estimated for emergence and germination (about 7% and 4%, respectively) whereas the lowest values (zero or close to zero) were obtained for *ervilha* and *manteiga* (both for emergence and germination), and for *sondeyoumbua* (for germination only). In all cases, the minimum loss (L_{min}) was always larger for emergence than for germination (as would be expected). Differences between E_f and G_f ranged from about 1% (*ervilha*, *manteiga* and *sam3*) to 6% (*sondeyoumbua*). The difference obtained for *sondeyombua* was sufficient to make the interval [I_1, I_2] for G_{soil} more extensive when compared to that obtained for E_{soil}, although the values of k and c_i were higher in E_{soil} than in G_{soil}.

The irrigation level corresponding to minimal losses (I_{min}) depended on the variety being studied. At emergence, it ranged from about 12 mm (*catarina*, *ervilha*) to about 15 mm (*manteiga* and *matuba*). At germination, it ranged from about 12 mm (*catarina*) to about 16-17 mm (*manteiga* and *matuba*). In no case, were the differences between the values found for emergence and germination statistically significant (95% confidence intervals for I_{min} always overlapped).

For each *m.a.l.* considered, I_1, I_2 and the range they delimit [I_1, I_2] for both germination and emergence also depended on the varieties studied. The minimum irrigation level that guarantees *m.a.l.* (I_1) for emergence ranged from 7.4 mm to 7.8 mm for the bean varieties and from 8.8 mm to 9.6 mm for the maize varieties. Values of I_1 for germination were slightly lower than those for emergence, ranging from 0.3 mm (*manteiga*) to 1.5 mm (*sam3*). The maximum irrigation level (I_2) that guarantees losses to the emergence below the *m.a.l.* was about 16-17 mm for the *catarina*, *ervilha* and *sondeyoumbua* and 19 mm for *manteiga*. Among maize varieties, I_2 was approximately 19 mm for *sam3* and greater than 20 mm for *matuba*. I_2 values for emergence are lower than the corresponding values for germination in four varieties (*catarina*, *ervilha*, *manteiga* and *matuba*) and slightly larger for the others. Among bean varieties, *manteiga* had the widest basins for both emergence (12.3 mm) and germination (18.2 mm) and *catarina* the narrowest (8.7 and 10.1 mm for emergence and germination, respectively). The irrigation interval lengths I_2-I_1 for maize varieties were similar for emergence (11 mm for *matuba* and 10.1 for *sam3*) but very different for germination (17.5 for *matuba* and 11.4 for *sam3*). Differences between I_2-I_1 for G_{soil} and E_{soil} ranged from 1 mm for *catarina*, *sondeyombua* and *sam3* to about 6-7 mm for *manteiga* and *matuba*.

Decreasing in losses at sowing from 6 mm to 9 mm was approximately linear (the initial phase of the curves shown in Figures 3, 4 and 5), regardless of whether water has been replaced (data not shown). Despite the small size of the dataset, this trend was statistically significant in most cases. However, the straight lines that reproduce the variation of losses in both cases were not significantly different (using Multiple Regression model to compare regressions). Furthermore, the actual trend of the losses at sowing whenever water is replaced was not clear, since in some cases the losses increase and in others they decrease. New experiments are suggested to increase the number of irrigation levels applied with periodic water replacement.

4. Discussion

For temperatures normally used in seed germination tests (from 20 to 30ºC), all varieties under study had minimal or even zero losses in many cases. In addition, the estimated minimum losses L_{min} were always larger than the maximum acceptable losses (*m.a.l.*) for all the varieties studied. Thus, the quality of the seed lots used was confirmed and the feasibility of the results obtained in this study sustained.

4.1. Observed variations in seed losses as a function of temperature and irrigation levels

The variation in seed losses, counted either at germination or emergence and on the two different substrates used (sandy loam-clay soil or filter paper) reveals a similar pattern if plotted against temperature, with optimal soil moisture conditions. Losses for any of the varieties studied are minimal along a broad thermal range (resembling a basin) and increase toward the lowest and highest temperatures use in each experiment. This means that temperature values close to those of the estimated base and maximum temperatures for maize and beans commonly referred to in the bibliography (for example, [28] and [47], respectively), by extending the residence time of seeds or seedlings in soil [48] drastically decrease, or even cancel, both the final emergence and germination.

For most of the varieties studied, the course of G_f-E_f observed over extreme thermal ranges showed that exposure to such temperatures was often insufficient to prevent germination, but enough to block the emergence. Too much time of exposure to soil pathogens in the upward path towards the soil surface may prevent the emergence of the seedling formed in the meantime. This then suggests, all else unchanged, the existence of different base and ceiling temperatures for both processes or at least the difficulty in defining common values for these two cardinal temperatures**.** Furthermore, the increase in losses at the extremes also has an impact on the calculation of the base temperature for emergence or germination and, consequently, on the quality of the linear fit suggested by several authors for the relationship between the respective rates and temperature [43, 49, 50].

Seed loss under optimal thermal conditions display a similar trend when plotted against irrigation levels, being nearly minimal along a broad range, increasing toward to both extreme levels used or only to the lowest irrigation values as in the cases of *manteiga*, *matuba* and *sam3*. This means that, both the insufficiency of water to surround the seed and a moist soil (to field capacity) at depths greater than that of the sowing can also affect the germination and emergence processes, either through the air permeability of soil or by the greater sensitivity of seeds to high water content in the soil. Also, the values of G_f-E_f suggested that exposure to such extremes irrigation levels allowed germination but was insufficient to guarantee the subsequent emergence. When the soil was 6 mm watered, the number of both non-emerged seedlings and non-germinated seeds was very high (only *sondeyombua* had interesting G_f values). With 7-8 mm watering there seemed to be a strong response from the germinative process but not, to a similar extent, of emergence (the differences between E_f and G_f reached their maximum at 7 mm, in 5 out of the 6 varieties). These differences were quickly attenuated for irrigation values above 8-9 mm, except in the case of *ervilha*.

4.2. Practical feasibility of the polynomial model used

The feasibility of a model is based both on its statistical robustness and the practical usefulness of its parameter values. In the present case, it is largely based on warnings and recommendations, considering the importance of factors such as soil type or substrate used in laboratory experiments. The polynomial functions suggested in Eqs. (2) and (3) appear to satisfactorily describe the course of seed losses as a function of both temperature and irrigation levels. Despite the number of events used in each experiment not being large, the good fits obtained in the different situations encourage their widespread use in modelling seed losses both at germination and emergence, either as function of temperature or irrigation level. The intersection of the polynomial function with the horizontal line defined by the maximum value of agronomically acceptable losses (*m.a.l.*) results, for each variety, in ranges of temperature $[T_1, T_2]$ and irrigation (or precipitation) $[I_1, I_2]$ over which losses are minimal. In tropical latitudes the importance of knowing $[T_1, T_2]$ and its limits (especially the lower endpoint) for each crop studied increases with altitude. In areas characterized by irregular rainfall, whether associated with high rates of water evaporation from the soil, the near-optimal interval $[I_1, I_2]$ enables the identification of appropriate levels of rainfall on dry soil (represented by different amounts of irrigation in the experiments carried out). Both the length and endpoints of those ranges are useful for farmers and other decision makers, whether when choosing crops or varieties to be used or in supporting decisions such as sowing times for a given crop or variety, using farm weather forecast and warning systems. Since these ranges and their endpoints are closely related to factors as the proximity to the sea and the altitude, respectively, they can also contribute to the agro-climatic zoning of a given territory.

The different parameters estimated from even-degree polynomial functions applied to experiments under optimal hydric (k, c_t, L_{min} and T_{min}) or thermal conditions (k, c_i, L_{min}, and I_{min}) varied with the varieties studied, the stages of development (germination and emergence) and the substrate used in germination experiments (G_{soil} or G_{FP}). Important technical and economic implications can be deduced from the variability of each of these parameters.

The estimated values of minimum losses, L_{min}, for the six varieties in different experiments can highlight the relevance of the substrate used (G_{soil} *vs.* G_{FP}) as well as their sensitivity to fine textured soils. The soil water content considered adequate for crop development (90% of soil-water availability) when temperature is the independent variable is debatable. Although the differences between estimated values of L_{min} are not statistically significant in most cases (based on the overlapping of 95% confidence intervals), some relevant characteristics are observable. Under soil water conditions initially taken as adequate (top 5.4 cm of moist soil for a sowing depth of 2 cm and filter papers permanently wet) minimum losses for each variety along a fairly broad thermal range depended on the substrate used (L_{min} was significantly different in both cases) and, for a given substrate, it varied with the variety used (with greater amplitude in G_{soil} than in $G_{FP,}$). The use of filter paper as a substrate for germination tests seems to favour maize varieties more than beans. There is a need to improve the statistical robustness of the results by increasing the number of seeds involved in G_{soil}. Furthermore, the optimal ratio between air and water surrounding the seed which varies between crops and their respective varieties [51], deserves further study. The filter paper method for germination tests may be questionable, including its improvement in technical terms.

Different degrees of adaptability to the soil used were found among the six varieties studied, either in the germination process or in the seedlings' rise to the soil surface. Soils with a low rate of oxygen diffusion such as the ones used in this study [52, 53], appear to unfavourably affect the final emergence of *sondeyombua* and *sam3* (high values of L_{min} for E_{soil} and G_{soil} much higher than G_{FP}) but not those of *catarina*, *ervilha* and *manteiga* (zero or very low value of L_{min} for G_{soil} and E_{soil} but clearly less than for G_{FP}). *Matuba* had similar adaptability to both substrates. With considerably more losses between germination and emergence, the rise of the *sondeyombua* seedlings towards the soil surface proved to be more sensitive to this type of soil than the other varieties. Different options should be taken depending on the behaviour of each variety. For example, increasing the number of seeds sown or sowing at a lower depth can be solutions for *sam3* and *matuba*, respectively. Both options can be recommended for *sondeyombua*.

When these L_{min} were compared with those estimated under optimal thermal conditions (Table 4), generalized decreases were observed, especially for *sondeyombua* and *sam3*. When I_2 values obtained for the different varieties are considered, we find that the initial moisture values considered to be optimal (top 5.24 cm of soil moistened, equivalent to approximately 21.2 mm of precipitation on dry soil) in the experiments in which the temperature was the independent variable are unclear. An important interaction between temperature, moisture and air permeability of soil must affect the diffusion rate of oxygen. This should be evaluated in order to achieved the optimal combination for each crop.

Since both T_{min} and I_{min} are midpoints of relatively wide near-optimal thermal plateaus they can be usefully replaced by the intervals. The higher the values of c (c_t or c_i) and k, the less the dependence of the length of both [T_1, T_2] and [I_1, I_2] on the value of *m.a.l.*. Since the *m.a.l.* for each crop varies from region to region, it is not appropriate to compare those thermal and irrigation ranges of the bean varieties with those of maize, but also identical weather forecasts can imply different levels of alert. The use of Eq. (1) with L_{min} = 0 (as was done in some cases) would provide an easier comparison between varieties of the same crop, but tends to worsen the goodness of fit.

Given the relationship between these parameters and climatic factors such as proximity to the sea (T_2-T_1) and altitude (T_1, I_1 and I_2), the results obtained prove to be useful for agro-climatic zoning. The smaller the thermal interval length (T_2-T_1) of a crop, the smaller its adaptability to regions further away from the coast. Therefore, more difficulties in emergence in areas farther from the sea are likely to be experienced by *catarina and* s*ondeyombua* than *ervilha* and *manteiga* and by *sam3* than *matuba*. The lower endpoint T_1 can contribute to agro-climatic zoning at altitude. For example, the emergence size of *ervilha* (T_1=13.5ºC) can be more expressive in areas at greater altitude that those of the other bean varieties studied (T_1 ranging from 16.1ºC to 18.5ºC). Likewise*, matuba* (T_1=17.2ºC) is expected to emerge more abundantly at higher sites than the *sam3* (21.1ºC).

Among bean varieties studied, *manteiga* is the best adapted to soil moisture variations in its initial stage of its development, thus gaining a competitive advantage over the rest. Although all bean varieties need only 7-8 mm of precipitation or watering to emerge or germinate to satisfactory levels, *manteiga* appears to be much less sensitive to greater wetted soil thicknesses (other varieties revealed substantial losses for irrigation allocations greater than 17-18mm). Comparing with *sam3*, *matuba* requires more rainfall (at least 10 mm of precipitation on dry soil) to ensure successful emergence. The behaviour of *matuba* for higher irrigation amounts is similar to that of *manteiga* (the range of water added was not sufficient to accurately know the values of I_2 for both varieties, that is, to rigorously evaluate the maximum precipitation from which it is possible to expect a significant increase in losses). Expanding in new experiments the domain of the function (100-E_f)% = f (I), mainly for higher irrigation values, will allow the I_2 values for these two varieties to be calculated more rigorously.

The influence of the soil on the emergence of crops is expressed in conditions that provide seed germination and the seedlings' rise to the surface. Here only the influence of soil on post-germination was highlighted. In the context of this work, it means understanding the differences observed between G_f and E_f. Under ideal conditions of soil water, *catarina*, *sondeyoumbua* and, to a lesser extent, *sam3*, seem more sensitive to the soil in the post-germinative phase, whereas *ervilha* seems to be less affected. For these varieties, decreasing the sowing depth can be an option whenever the soil temperature approaches the values that delimit the corresponding basin (T_1 and T_2). The role of the soil under optimal thermal conditions seems to be less significant than for other varieties. In any case, the differences G_f.-E_f were especially relevant for the extreme values of temperature and irrigation (except for *sondeyombua*, the emergence of germinated seeds is an almost certain event along fairly broad thermal or irrigation ranges). This can have added practical relevance whenever the thermal environment approaches T_1 or T_2. C*atarina*, *ervilha* and *manteiga* beans seem to clearly benefit from the soil substrate, while *sam3* thrived in a paper filter substrate, with lower L_{min} and longer [T_1, T_2]. On the contrary, *matuba* was benefited slightly in G_{FP} (longer [T_1, T_2] but similar L_{min}) whereas *sondeyombua* showed different trends for L_{min} and [T_1, T_2]. The differences between T_2-T_1 obtained in G_{soil} and G_{FP} were even greater for *ervilha* and *manteiga* than those found between G_{soil} and E_{soil}. Different levels of contact between water and seeds may be the basis of the differences found in the results obtained for the two types of substrate used.

5. Conclusions

For each crop or variety, sowing losses depend on both soil temperature and thickness of the soil initially moistened. In addition, the substrate used to test the final germination of crops can also be relevant in the level of losses.

Seed losses were minimal along a broad thermal or irrigation ranges and increased toward the extremal temperatures and, in general, also towards the extreme irrigation levels considered. Thermal [T_1, T_2] and irrigation [I_1, I_2] ranges along which losses are nearly minimal, were successfully identified using even-degree polynomial models. The endpoints and length of those ranges were found to be crop-dependent.

Both the lengths of those ranges and their endpoints can be interesting for decision-making regarding crops or varieties to be installed or sowing times for a given crop or variety. Farm weather forecast, warning systems of different nature and agro-climatic zoning can also benefit from the knowledge of these parameters.

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