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Groundnut seedling emergence in relation to thermal-time and soil water

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RESUMO

A medição do efeito de várias combinações de temperatura e água do solo sobre a emergência do amendoim permite verificar que as curvas de emergência relativamente à acumulação de temperatura são bem descritas por funções logísticas que se interpretam como curvas de probabilidade acumulada. Tais curvas permitem determinar facilmente o tempo–térmico para 50% da emergência final, a dispersão da emergência e a duração–térmica para ocorrência duma emergência de 80% da final.

Verifica-se que estes parâmetros são praticamente invariantes (relativamente ao tempo, à temperatura e à água) para teores de água no solo superiores a 45% da capacidade de campo e temperaturas inferiores à óptima para a emergência, pelo que a sua medição pontual é representativa para toda esta gama de condições ambientais.

RÉSUMÉ

Les courbes d'émergence des cacahouètes en fonction du temps–thermique et du contenu en eau du sol sont analysées en utilisant une equation logistique interprétée comme une courbe sigmoide de probabilité cumulative. Cette equation decrit bien la variation de l'émergence cumulative en fonction du temps–thermique et est utilisée pour estimer la taux d'émergence, l'étalement de l'émergence et le temps–thermique de l'émergence sur le terrain.

Le concept de l'invariabilité du temps–thermique pour 50% d'émergence finale, de l'étalement de l'émergence et de la durée d'émergence sur le terrain est démontré pour une vaste gamme de températures ambiantes et de contenus en eau du sol.

SYNOPSIS

Emergence curves of groundnut in respect of thermal-time and soil water content are analysed using a logistic equation interpreted as a sigmoid curve of cumulative probability. This equation describes well the thermal-time course of cumulative emergence and is used to estimate the speed of emergence, the spread of emergence and the thermal-time for field emergence.

It is shown that the concepts of an unique thermal-time for 50% final emergence, the spread of emergence and the thermal-duration of field emergence are applicable over a large range of soil water contents and ambient temperatures.

1. INTRODUCTION

Seedling emergence is the first stage in successful crop establishment and hence a major factor determining crop yield in the field. Consequently, agronomists are concerned with methods to evaluate emergence. Standard tests of seed viability and seed vigour are frequently used for this purpose. However, tests of seed viability measure only the success of germination (or emergence) at a single fixed set of conditions. Tests of seed vigour, although aimed to represent the behaviour of a seed lot in the field (Perry, 1981; Hampton and Coolbear, 1990), only assess the *relative* performance of several lots and the information they provide can be further limited by interactions between the rate and success of germination (see below). The specification of seed vigour has been reviewed recently by POWELL (1988) and HAMPTON and COOLBEAR (1990). However, a method for evaluation of emergence performance in the field should give *quantitative* information on the three parameters of emergence which are significant factors in crop establishment: the "success" or size of the emerged population; the "speed" or rate of emergence; and the "spread" or duration of emergence (JANSSEN, 1973; ABREU, 1987). In addition, it should be reproducible over the wide range of soil water and temperature regimes which characterize the field environment.

Studies on the emergence and vigour of groundnut (*Arachis hypogaea* L.) in relation to the combined effects of soil temperature and soil water have emphasized the need for a method to describe fully the thermal-time course of emergence (ABREU, 1987). Analysis of emergence in relation to thermal-time, rather than clock-time, enables the effects of soil water to be separated from those of temperature (GARCIA-HUIDOBRO, 1982; ABREU, 1987). Application of the thermal-time concept to emergence has been based on the single measurement of the thermal-time for emergence, defined as the temperature accumulated above the base temperature (for germination) from sowing to 50% emergence of seeds sown (FEDDES, 1971; ANGUS, CUNNINGHAM, MONCUR and MACKENZIE, 1981; GARCIA-HUIDOBRO, MONTEITH and SQUIRE, 1982; MOHAMED, 1984). However, this neglects information on the size of the emerged population and, particularly, on the spread of emergence in time. In addition, the use of 50% of seeds *sown* results both in the neglect of values of final emergence of less than 50%, which present useful information on treatment effects (SCOTT, JONES and WILLIAMS, 1984), and exaggerates slow rates of emergence. When studying the emergence responses of a cultivar across its complete range of tolerance, a better indicator of the speed of emergence is the thermal-time for emergence of half of the emerged population, θ_M (d°C). HSU and NELSON (1986) and MUENDEL (1986) have used the same criterion to define the clock-time for emergence.

Fitting curves to emergence data is useful to provide information on the emergence parameters: time (and rate), spread and cumulative emergence (JANSSEN, 1973; BOULD and ABROL, 1981; HSU, NELSON and CHOW, 1984; SCOTT *et al.*, 1984; BROWN and MAYER, 1988). The several types of equations used for analysis of germination and emergence data have been reviewed by SCOTT *et al.* (1984) and BROWN and MAYER (1988). Logistic-type equations, often used to describe the growth of populations, have been applied successfully to studies of seed germination in relation to *clock-time* – eg. by JANSSEN (1973), SCHIMPF, FLINT and PALMBLAD (1977), HSU *et al.* (1984) – and have also been used in the analysis of seedling emergence (eg. HSU and NELSON, 1986). The statistical and biological reasoning supporting the use of logistic equations was discussed by JANSSEN (1973), SCHIMPF *et al.* (1977) and HSU *et al.* (1984).

Surprisingly, a limited amount of work has been published on the combined action of soil water and temperature on emergence. This paper deals with the analysis of emergence curves of groundnut in respect of thermal-time and soil water using a logistic equation. The function employed assumes that the time distribution of emergence presents a bell–shaped probability function in thermal-time, peaking at θ_M. Emergence data were measured for combinations of soil water and soil temperature representing the realistic range encountered in the field, so that the effects of soil water on both the thermal-time for emergence and the spread of emergence could be estimated from the logistic data fitted at different temperatures.

2. MATERIAL AND METHODS

EMERGENCE DATA

The data analysed in this paper are the results of measurements of emergence of groundnut seedlings (cv. Kadiri 3) described by ABREU (1987). Briefly, measurements of emergence were made on a temperature controlled propagation–bench, under ten soil water contents (from 5% to 100% field capacity, FC) for each of five constant soil temperatures (20°C, 25.4°C, 30°C, 32°C and 36.9°C). At field capacity the gravimetric water content of the sandy-loam soil used was 25.3 g water per 100 g oven–dried soil; the dry soil bulk density was 1.43 t m^{-3}, similar to that *in situ*. Seeds were sown 5 cm deep and 10 cm apart in aluminium boxes filled with soil and housed in the bench. Forty seeds were used for each temperature/water combination. Emergence was counted three times a day until the experiments ended at the third consecutive day without progression on the records.

DATA ANALYSIS

Emergence data were analysed on the assumption that the "instantaneous" thermal-rates of emergence $dM/d\theta$, with units % $(\mathrm{d}^\circ\mathrm{C})^{-1}$, are well described by an equation similar to that discussed by CAUSTON (1977),

$$dM/d\theta = kM(1 - M/M_T) \quad (1)$$

where M (%) is the cumulative emergence at the accumulated thermal-time θ (d°C), M_T is the final emergence and k, with units of $(\mathrm{d}^\circ\mathrm{C})^{-1}$, is an empirically derived constant representing the relative thermal-rate of emergence and related to the spread of emergence (see below). Equation 1 can be considered to define a bell-shaped probability function which is symmetrical about θ_M, the thermal-time at which the corresponding rate of emergence is a maximum. It follows that when $\theta = \theta_M$, $d^2M/d\theta^2 = 0$ and $dM/d\theta = kM_T/4$. θ_M is the mean (or most probable) thermal-time for emergence – the thermal-time when seedlings are emerging with greatest frequency under the prevailing environmental conditions. In addition to the description of the "instantaneous" emergence thermal-rates, Eq. 1 provides a simple way to quantify the speed, the spread and the size of emergence at different elapsed thermal-times.

The integration of Eq. 1 with respect to θ produces the logistic function

$$M = M_T/(1 + b\exp(-k\theta)) \quad (2)$$

where b is an empirically derived constant. Equation 2 can be considered as a sigmoid curve of cumulative probability, similar in shape to the integrated normal function, which describes the thermal-time course of cumulative emergence. Theoretically, the asymptotes are $M = 0$ when $\theta = -\infty$ and $M = M_T$ when $\theta = +\infty$. The inflexion point of this logistic equation is $(\theta_M, M_T/2)$, where θ_M represents the thermal-time required for cumulative emergence to be half of the *final* emergence, rather than half of the seeds *sown*. It can be shown that $\theta_M = (\ln b)/k$. When M_T is known, the constants b and k can be obtained by a linear regression of $\ln(M_T/M - 1)$ on θ, since the linearizing transformation of Eq. 2 is

$$\ln(M_T/M - 1) = -k\,\theta + \ln b \quad (3)$$

The distribution of $dM/d\theta$ also provides information on the spread of the thermal-times of emergence around the mean. The two inflexion points of $dM/d\theta = f(\theta)$, calculated as $d^3M/d\theta^3 = 0$, occur when

$$\theta = \theta_M \pm (\ln(2+\sqrt{3}))/k \tag{4}$$

At these points $dM/d\theta = kM_T/6$. By analogy with the normal distribution, the quantity $(\ln(2+\sqrt{3}))/k$ can be interpreted as equivalent of the "standard deviation" and is a convenient measure of the spread of emergence (σ_M).

The integral of $dM/d\theta$ between particular values of thermal-time predicts the corresponding fractions of final emergence, while the total area under the $dM/d\theta$ curve is M_T. This area may be considered as unity if M is normalized as M/M_T. The area of $dM/d\theta$ between the two inflexion points is

$$\int_{\theta_M-\sigma_M}^{\theta_M+\sigma_M} dM/d\theta \cdot d\theta \tag{5}$$

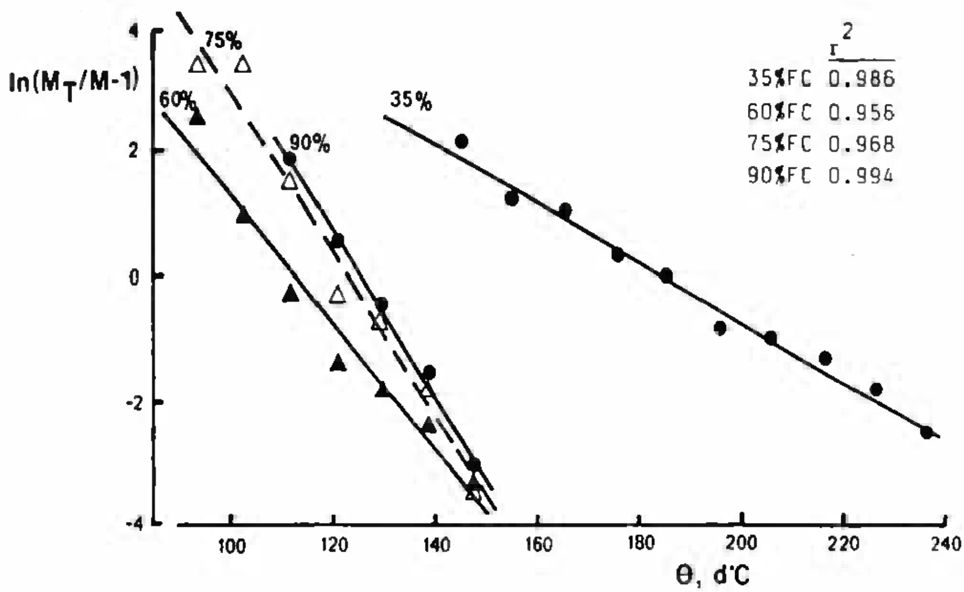
and equals $0.577\,M_T$, compared with 0.683 between $\pm$ one standard deviation either side of the mean in the normal distribution. Therefore, the fastest emerging 60% of the final population (from about $0.2\,M_T$ to $0.8\,M_T$) will emerge in a thermal-time of $2(\ln(2+\sqrt{3}))/k$. A useful criterion for "Field Emergence" (MUENDEL, 1986) is a stand of about 80% of the final density; this is reached at an elapsed thermal-time (θ_{80}) equal to θ_M plus one "standard deviation", since

$$\int_{-\infty}^{\theta_M+\sigma_M} dM/d\theta \cdot d\theta = 0.79\,M_T \tag{6}$$

3. RESULTS

For assessment of the standard of fit of the logistic assumption, Eq. 3 was fitted to each emergence curve of groundnut. Representative results are shown in Fig. 1 for emergence at 20°C on the propagation bench. For all experiments the goodness of fit was always better than the 1% significance level (in 80% of the cases at 0.1%), showing that the logistic assumption offers a good description of cumulative emergence.

FIGURE 1 – *Logarithmic transformation of the logistic fittings to the thermal-time course (θ, d°C) of cumulative emergence (M, %), at 20°C and gravimetric soil water contents of 35%, 60%, 75% and 90% field capacity. M_T is the final emergence. Also shown are the coeficients of determination (r^2) of each line.*



The final emergence was strongly affected by both soil water content and temperature, as shown in Fig. 2. The best final emergence (70% to 80% of seeds sown) at each temperature occurred in a range of soil water contents from 45% to 75% FC, with high temperatures shifting the best M_T values towards the dry end of this range. For higher and lower soil water contents, the final emergence decreased to values frequently below 50% of seeds sown. Reduced final emergence in "too" dry and "too" wet soils has been reported in the literature for other crops, particularly vegetable crops (Doneen and MacGillivray, 1943; Feddes, 1971). Figure 2 also shows that for temperatures below the optimum for groundnut emergence, which is about 30–32°C (Abreu, 1987), the dependence of M_T on soil water content above 50-60% FC was practically independent of temperature.

FIGURE 2 – *The relationship between final emergence (M_T, % of seeds sown) and gravimetric soil water content (Θ, % of field capacity, FC) at the soil temperatures shown.*

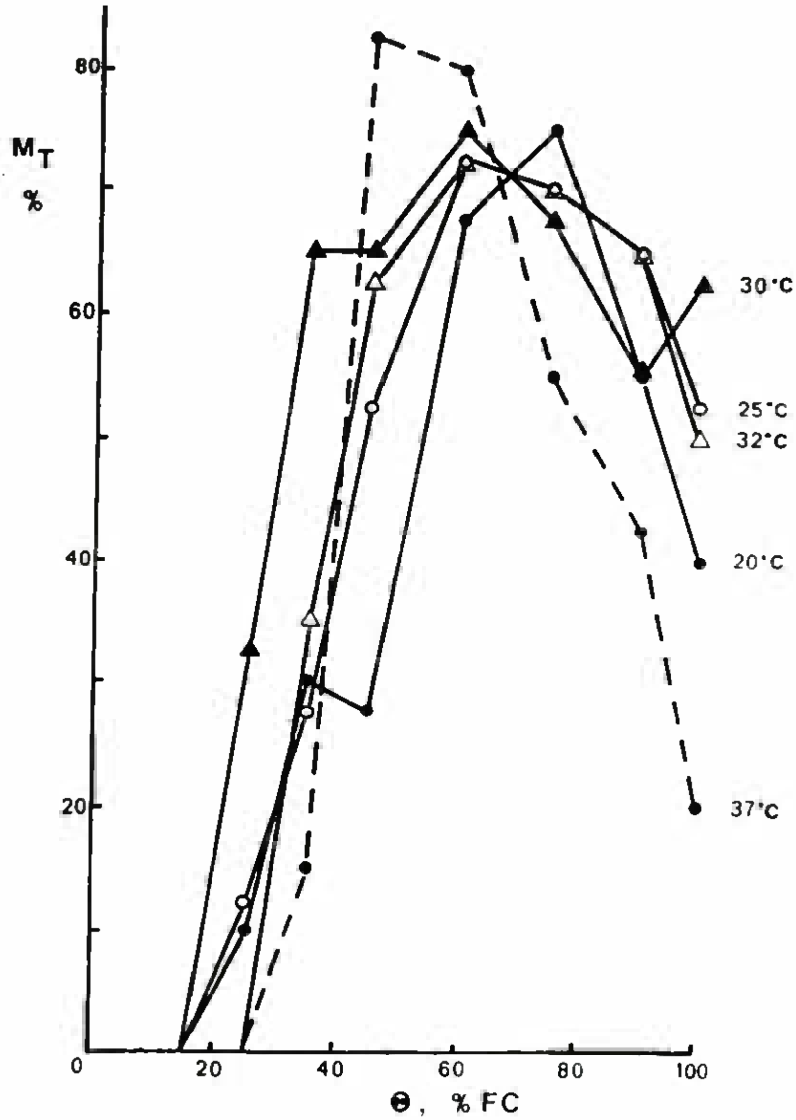
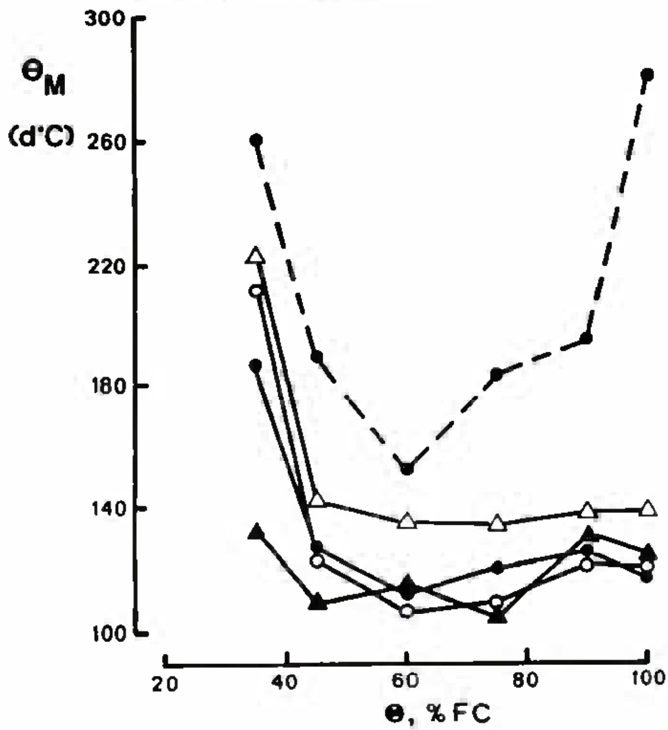


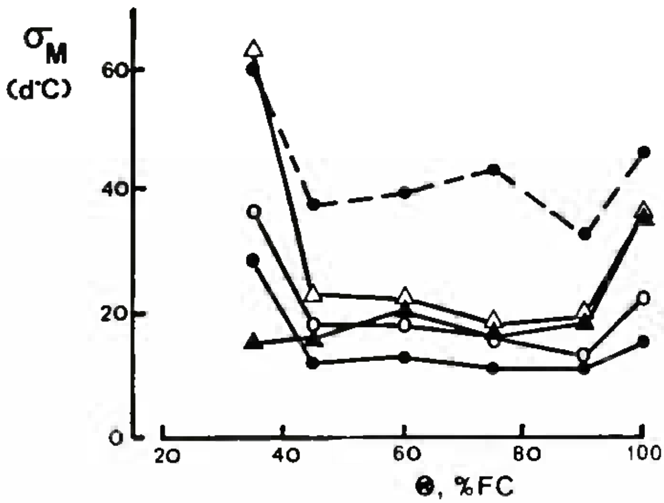
Figure 3 shows the dependence of the estimated thermal-times for emergence on soil water content. For temperatures below the optimum, θ_M was independent of both soil temperature and soil water for contents above 45% FC. In these conditions, θ_M averaged 122 d°C with a standard deviation of 11 d°C. The base temperature used for the calculations was 10.5°C, obtained by MOHAMED (1984) for germination of the same cultivar. However, θ_M increased to almost double the above value in drier soil. These results are similar to those reported by FEDDES (1971) for emergence of radish, garden beet, spinach and broad-beans, by GARCIA-HUIDOBRO (1982) for pearl millet and by RAO and DAO (1987) for emergence of five Brassica cultivars at a soil temperature of 7.5°C and five soil water potentials from −10 kPa to −500 kPa. At 37°C, the thermal-times required for emergence of groundnut in wet soil were also much higher than those for temperatures below the optimum.

FIGURE 3 – *Dependence of thermal-time for emergence (θ_M) on soil water content (Θ) at several soil temperatures. (Symbols as in Fig. 2).*



As indicated previously (Eq. 4), the spread of emergence was estimated for each $M(\theta)$ curve as $(\ln(2-\sqrt{3}))/k$, the "standard deviation" of the distribution of $dM/d\theta$ with θ. The dependence of this quantity on soil water content and temperature is shown in Fig. 4. For temperatures below the optimum and soil water contents between 45% FC and 90% FC, σ_M was similar for all treatments, with a mean value of 17 ± 4 d°C. However, the spread of emergence increased to about 2.5 times this value at 37°C. For soil water contents outside the range 45% to 90% FC σ_M was larger in dry than in wet soils, except at 30°C.

FIGURE 4 – *Dependence of spread of emergence (σ_M, in thermal--time units) on soil water content (Θ) at several soil temperatures. (Symbols as in Fig. 2).*



The combined effects of temperature and soil water content on the thermal-times for "field emergence" (Eq. 6) can be derived from Figs. 3 and 4, since θ_{80} is the summation of corresponding values of θ_M and σ_M. In pratical terms, for temperatures below the optimum and soil water contents between about 45% and 90% FC, θ_{80} can be considered almost independent of both temperature and water, with a value of about 140 d°C. Drier soils and above optimum temperatures increase θ_{80} sharply.

4. DISCUSSION

The thermal-time course of cumulative emergence of groundnut is well described by a logistic type equation of cumulative probability, the parameters of which can be used to characterize emergence. In particular, the final emergence, the thermal-time to emergence, the spread of the emergence thermal-times and the thermal-time for "field emergence" are easily obtained from such equations. This approach has two additional advantages: it can accomodate measurements with a final emergence below 50% of seeds sown, so that valuable information on treatments effects is not discarded, and it avoids confounding survival with vigour.

There are reports in the literature of the use of several types of equations to describe the time course of seedling development, mainly germination, but none have been used for analysis of the thermal-time requirements. For example, JANSSEN (1973) and SCHIMPF *et al.* (1977) used a logistic-type approach to analyse the germination of *Veronica arvensis* L., and *Setaria lutescens* (Weigel) and *Amaranthus retroflexus* L. in chronological time. HSU *et al.* (1984) also used a logistic equation to develop a model for germination of *Sorghastrum nutans* L., which was then applied successfully to the emergence of the same cultivar in the field (HSU and NELSON, 1986). Their model assummed that the instantaneous rates of germination (and emergence) at each temperature were approximately normally distributed in clock-time, peaking at the time required for 50% emergence of seeds sown. In contrast, equations which accomodate skewed data were used by MILTHORPE and MOORBY (1979) and discussed by BROWN and MAYER (1988), since germination is sometimes positively skewed (NICHOLS and HEYDECKER, 1968; SCOTT *et al.*, 1984; BROWN and MAYER, 1988). However, most of the skew equations make the simplifying assumption that the instantaneous germination rate decreases continuously with time, from a maximum at the time germination starts. This may be realistic for fast germinating seeds, particularly at temperatures close to their optimum (SCOTT *et al.*, 1984), but SCHIMPF *et al.* (1977) considered a logistic function of the type used in the present work a good fit for both fast and slowly germinating seed populations. There seems no reason to suppose that a particular type of skewness is a consistent characteristic of either germination (GOODCHILD and WALKER, 1971) or seedling emergence (ORCHARD, 1977). In addition, emergence is a longer process than germination, particularly with large seeds like groundnut, and is subject to a wider range of environmental constraints. Since there is no reason to believe that the emergence curves should be of any particular shape, logistic functions appear appropriate where they are a good fit to the data.

Analysis of emergence curves in relation to thermal-time, rather than clock-time, allows the effects of temperature on emergence to be decoupled from those of other environmental factors, as used by GARCIA-HUIDOBRO (1982) and SQUIRE and ONG (1983) to uncouple the effects of temperature and water on emergence and leaf extension of pearl millet. In addition, use of thermal-time allows analysis of emergence in conditions of fluctuating temperature, when the use of clock-time is very difficult (BROWN and MAYER, 1988).

A further advantage of the use of thermal-time is shown by the results presented in Figs. 3 and 4. The concepts of an unique thermal-time for 50% final emergence, the spread of emergence and the duration of field emergence are applicable over most of the range of soil water contents and ambient temperatures. For example, the measurement of these three parameters at a soil water content of 60–75% FC is adequate to characterize the behaviour of groundnut emergence in relation to time, temperature and water for temperatures below 30–32°C and soil water contents above 45% FC. Assuming an average temperature of 27.5°C, half of the viable seeds will emerge in about 7 days after sowing, while field emergence will take one more day. Consequently, the final emergence as a proportion of seeds sown (%) and the thermal-time for field emergence (80% of final emergence) may provide useful parameters to characterize seed performance in the field.

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