Modelling the emergence pattern of six summer annual weed grasses under no tillage systems in Argentina

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Summary

Field trials were established in various growing seasons in four experimental sites with soyabeans or maize grown under no tillage systems. Seeds of *Digitaria sanguinalis, Eleusine indica, Sorghum halepense, Setaria geniculata, Echinochloa colonum* and *Urochloa platyphylla* were incorporated in surface soil, under the crop residues of the previous season, each autumn. Regular records of seedling emergence during the following spring and summer were used to model the pattern of each species as a function of the thermal time in the 2 cm upper layer of the soil profile. A Weibull function closely described ($r^2 = 0.73–0.93$) the relationship between thermal time and seedling emergence for all species in each site and year. The coefficient of determination for the model verification ranged from 0.71 to 0.98. Species may be grouped into three emergence time-span groups. *Eleusine indica, U. platyphylla* and *E. colonum* had a long-lasting emergence, requiring 940–1660 d°C (growing day degrees) to complete this process. *Digitaria sanguinalis* and *S. halepense* had an intermediate emergence time-span, completing this process in 540–1090 d°C. *Setaria geniculata* exhibited the shortest emergence time-span (290–660 d°C required for full emergence). Different hypotheses were tested in order to explain species model parameter differences in different sites and to establish the basis for more refined models with improved prediction capabilities.

Keywords: Weibull function, seedling emergence, thermal time, herbicide decisions, *Digitaria sanguinalis, Echinochloa colonum, Eleusine indica, Setaria geniculata, Sorghum halepense, Urochloa platyphylla.*

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Introduction

Seedling recruitment is the first process in the life cycle of annual weeds and all the subsequent demographic processes are based on this. Because of this, recruitment prediction is a very important element in the forecast of life history behaviour for weed management (Cousens & Mortimer, 1995). Although weed emergence patterns have been studied since the early 1960s (Roberts, 1964; Roberts & Feast, 1970; Leguizamón *et al.*, 1980, 2005; Leguizamón, 1986; Egley & Williams, 1991; Anderson & Nielsen, 1996), only recently has research focused on understanding the seasonal changes in dormancy and germination, the two processes which underlie the periodicity of seedling emergence (Forcella *et al.*, 2000).

Seedling emergence events at the field scale are the consequence of the probability of certain meteorological conditions suitable for dormancy release, germination and emergence. Semi-empirical approaches have proved to be very useful for forecasting the development of various pest organisms (Finch *et al.*, 1996). In the case of weeds, the frequency distribution of rainfall and other meteorological events have been used to predict the patterns of weed emergence (Grundy & Mead, 2000).

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Population-based threshold models appear to have the potential to provide a universal approach to quantifying the array of ecophysiological responses. The models, which were first developed from thermal time (e.g. Garcia-Huidobro *et al*., 1982), describe the effects of temperature on the germination rate using linear relationships. To account for the effects of reduced water potential, the hydro-time concept was proposed (Bradford, 2002) as a refinement and extension of thermal time. However, fluctuations in soil water content can also affect the dormancy status of seeds (Battla & Benech-Arnold, 2006; Chantre *et al*., 2008). Moreover, dormancy release and germination are not constrained by just these two factors. The processes may be further influenced by other environmental factors, particularly light (Batlla *et al*., 2004; Batlla & Benech-Arnold, 2005; Fenner & Thompson, 2005; Finch-Savage & Leubner-Metzger, 2006).

The type and timing of tillage practices influences the distribution and the dormancy status of the seeds in the soil profile (Mohler, 1993; Forcella *et al*., 1997). A reduction of tillage increases the amount of crop residues on the soil surface (Buhler *et al*., 1994), altering the soil microclimate and creating a variety of conditions that affect weed germination. These microsite changes result in long-term changes to the weed flora (Dorado *et al*., 1999). In general, large-seeded broad-leaved weeds become less of a problem in reduced tillage systems, whereas small-seeded broad-leaved weeds and grasses become more important weeds under no tillage. In Argentina, more than 70% of the arable land is managed under no tillage, a system claimed to reduce soil erosion and increase water conservation in the soil, a key issue in non-irrigated extensive crops (Leguizamón, 2001). In these systems, weed control is highly dependent on herbicides. The availability of predictive tools for weed emergence and growth, based on simple and already available meteorological records, will allow the optimisation of herbicide usage. Herbicide optimisation is an increasingly important goal for environmental and economic reasons.

The objective of this study is to develop and validate empirical mathematical models of the emergence pattern of six grass species: *Digitaria sanguinalis* (L.) Scop., *Echinochloa colonum* (L.) Link., *Eleusine indica* (L.) Gaertn., *Setaria geniculata* (Lam.) Beauv., *Sorghum halepense* (L.) Pers. and *Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster. These weeds have increased their frequency in extensive summer crops managed under direct drilling in Argentina and frequently dominate weed communities in such systems (Leguizamón *et al*., 2006).

Methods

Field experimental data

Field experiments were conducted at four sites located in the rolling Pampa with a sequence of maize and soyabean grown under no tillage systems (Table 1). The most recommended cultivars of these two crops were direct drilled in rows 0.52 m apart in mid-September for maize and mid-November for soyabeans, at standard densities each year. Nitrogen fertiliser (UAN) was applied before planting maize crops each year. Both maize and soyabean were treated with recommended insecticides each year. Crop yields (not shown) were within the average for all sites per year.

Caryopses plus lemma and palea (hereafter referred to as ‘seeds’) from mature plants of *D. sanguinalis, E. colonum, E. indica, S. geniculata, S. halepense* and *U. platyphylla* were collected from several local sources in each experimental site at the end of each summer season. These seeds were sieved and cleaned using an air blower and thereafter stored for 2 months in paper bags at laboratory temperature (22°C).

A strip of 6 × 150 m was marked out at every site during the winter fallow. Polyvinylchloride cylinders (30 cm diameter 6 cm height) were placed 3 m apart and dug 4 cm into the soil along three of the future inter-rows of the summer crops. These inter-rows were selected in order to avoid tractor wheels passing over

Table 1 Location, soil properties and crops grown in each site per year

Site	1 Manfredi	2 Rio IV	3 Villegas	4 Zavalla
Lat.; long.	31°55′; 63°55′	33°04′; 64°38′	34°46′; 62°59′	33°01′; 60°01′
Soil type	Silty loam	Sandy loam	Sandy clay-loam	Silty loam
Clay (%)	15	13	25	25
Silt (%)	30	23	26	70
Sand (%)	15	64	49	5
OM (%)	2.5	1	2	3
Crops				
00–01	Maize	Soyabean	Maize	Soyabean
01–02	Soyabean	Soyabean	Soyabean	Maize
02–03	Maize	–	–	Soyabean
03–04	Soyabean	–	–	Maize

the cylinders at planting. Each soil cylinder was treated with methyl bromide in order to diminish the native soil seedbank. After 72 h, 150 (year 1) to 500 seeds (years 2–5) of each species were gently distributed among the crop residues in the first 1 cm of topsoil, simulating the natural seed rain. Seed incorporation into the soil was made during late autumn (May–June) each year. Three replicates (cylinders) placed at random were assigned to each species in each site per year. Destructive seedling counts were made weekly from 1 August in sites 1, 3 and 4 and every 15–20 days in site 2, until February–March, depending on the species and site per year.

Although the total number of site per year considered was 14, some species were not present (or presented low densities) in some sites. Consequently, the number of data sets available for each species ranged from 13 (in the case of *S. halepense*) to six (in the case of *S. geniculata*). In all cases (except for *U. platyphylla*), the last data sets were not used for building models and were left for model validation. Daily maximum and minimum air temperature and rainfall data were obtained from weather stations located close (<1 km) to the experiments.

Modelling procedures

Seedling recruitment data were tabulated, calculating the proportion of plants emerged in each period in relation to total emergence. The core of the program WeedCast (Archer *et al.*, 2001) was used to calculate the daily soil temperature which was estimated at a soil depth of 2 cm, based on the daily maximum and minimum air temperature, rainfall, type of soil, previous crop and tillage method. We then modelled the pattern of emergence based on calendar or thermal time using a Weibull function.

Calculation of thermal time

We calculated the accumulated thermal time (Θ_T, measured in growing day degrees, d°C) using species-specific temperature thresholds obtained for each species or a close relative from the literature (Table 2). To calculate d°C we used the mean–minus–base method (Leblanc *et al.*, 2003):

Table 2 Base temperature used for each species and source

Species	T_b (°C)	Reference
Digitaria sanguinalis	13.6	Steinmaus *et al.*, 2000
Echinochloa colonum	10	Wiese & Binning, 1987
Eleusine indica	12.6	Masin *et al.*, 2005
Setaria geniculata	10	Steinmaus *et al.*, 2000
Sorghum halepense	8.5	Benech-Arnold *et al.*, 1990a; b
Urochloa sp	13	Teuton *et al.*, 2003

$$\Theta_T = \Sigma_i^n[(T_{\max} + T_{\min})/2 - T_b] \qquad (1)$$

where i is the starting date to accumulate degree days (August 1st each site per year), n is the number of days for which d°C is calculated, $T_{\max}$ and $T_{\min}$ are the daily maximum and minimum temperatures and T_b is the base temperature for emergence. This method is accurate if the minimum temperature is above the base temperature. This is the case for these summer weed species, growing under increasing temperatures as the warm season progresses. We chose 1 August as the date to start to accumulate day degrees, because it is expected that at this time the cold of winter (June–July) will have released seed dormancy without allowing germination.

Modelling seedling emergence

The proportional emergence of seedlings recorded at each site per year was regressed against thermal time (d°C) using the following Weibull model:

$$\mathrm{CE} = 1 - \exp(-\ln(2)(t/a)^b) \qquad (2)$$

where CE is the cumulative proportion of emergence until day n after 1 August, and a and b are shape parameters. The model (eqn 2) was fitted to the data in following successive steps:

1. To have a preliminary description of the emergence process. We modelled the pattern of seedling emergence using the curve fitting-nonlinear regression menu of GRAPHPADPRISM software (GraphPad Software Inc., La Jolla, CA, USA). For this purpose, accumulated Julian days were used as independent variable instead of Θ_T.
2. To calculate d°C.
3. To assess the significance of a and b parameters and the goodness of fit of the model based on d°C.
4. To search for criteria for grouping the experimental data set and find explanations for parameter variation.

Model validation

Model validation was conducted by comparing the quality of the 'predicted' with 'observed' output values of models obtained in independent sites per year data, according to the species, by estimating the departure (at $P < 0.001$) of the parameters a (intercept) and b (slope) to 0 and 1, respectively, in the following model:

$$\mathrm{CE}_{(\mathrm{Pred})} = a + b \times \mathrm{CE}_{(\mathrm{Observed})} \qquad (3)$$

Results

Soil temperature and rainfall

Although there were site and year variations within the climatic data set, the average values for all the site per year offer a good description of the soil temperature and rainfall conditions prevailing during the experimental period. Average soil temperatures increased gradually during the first 180 days after August 1st (DAA). During the first 60 days, temperature ranged from 5 to 10°C, rising to 15°C during the following 70 days; from 130 to 165 DAA temperature ranged from 15 to 20°C, rising to 25°C from 165 to 215 DAA (Fig. 1A). Thereafter, temperature declined steadily. Rainfall was adequate during most of the experimental period, with only two dry periods, one at the end of winter (0–60 DAA) and another in the middle of the summer (180–210 DAA) (Fig. 1B). Therefore, conditions during most of the seedling emergence period (60–180 DAA) were characterised by temperatures ranging from 10 to 25°C and relatively abundant precipitations which ensured adequate water availability in the soil within the emergence time span of all species.

Seedling emergence

The average of the total number of seedlings emerged per sq. m per year were 5910, 2489, 2711, 848, 1696 and 576 for *D. sanguinalis, E colonum, E. indica, S. geniculata, S. halepense* and *U. platyphylla* respectively. The date for onset of seedling emergence (defined as 10% of total emergence) for all the species ranged from 49 to 60 DAA. However, the large CV obtained for all these values indicate a high variability within the data sets (Table 3). The Julian days required for 50% emergence ranged from 87 to 122 days and considerable variation was also observed among sites and years. The emergence period was nearly finished (> 95% emergence) within 160 days in all six species.

Using thermal time instead of Julian days removed much of the variation observed among years. The Weibull model closely fitted (r^2 = 0.73–0.93) the data for all species. However, significant differences in model parameters were found for a given species in the different sites. A site by site analysis led to the conclusion that models of sites 2 and 3 did not exhibit significant differences between them, while those for sites 1 and 4 stood out clearly. Consequently, models are presented for each species for sites 1–4 (where available).

Digitaria sanguinalis was one of the first weeds to emerge, requiring 80–280 d°C to reach 50% emergence (Table 4). Clear differences were found in the results

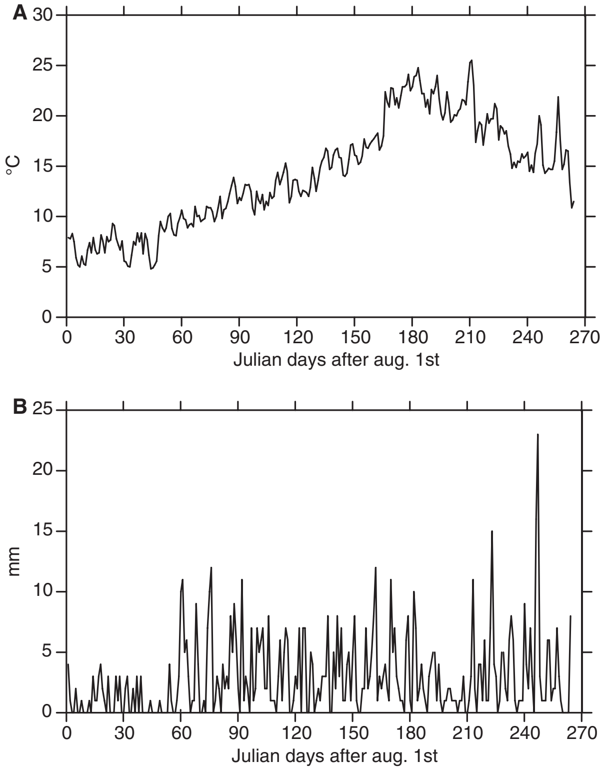

Fig. 1 Average soil temperature estimated by WeedCast (A) and daily rainfall (B) for all sites per year from August 1st.

Table 3 Calendar time (Julian days) for selected cumulative emergence times for the five species (average for all sites/locations)

	Julian calendar days since August 1st		
Species	10% emergence	50% emergence	90% emergence
Digitaria sanguinalis	60 (44)	109 (24)	129 (21)
Echinochloa colonum	49 (92)	87 (45)	108 (29)
Eleusine indica	50 (54)	122 (18)	156 (17)
Setaria geniculata	56 (71)	90 (31)	113 (15)
Sorghum halepense	54 (60)	115 (18)	147 (26)
Urochloa platyphylla	58 (21)	98 (12)	130 (15)

CV (%) in parenthesis.

Table 4 Growing degree days (d°C) required for selected cumulative emergence times for the six species using eqn (2) fitted model

		D°C required for		
Species	Site	25% emergence	50% emergence	75% emergence
Digitaria sanguinalis	1	210	280	360
	2 & 3	30	80	160
	4	90	150	250
Echinochloa colonum	1	220	330	460
Eleusine indica	1	330	420	520
	4	360	580	850
Setaria geniculata	2 & 3	140	200	250
	4	90	150	250
Sorghum halepense	1	240	290	350
	2 & 3	180	270	360
	4	290	500	780
Urochloa platyphylla	1	40	100	190

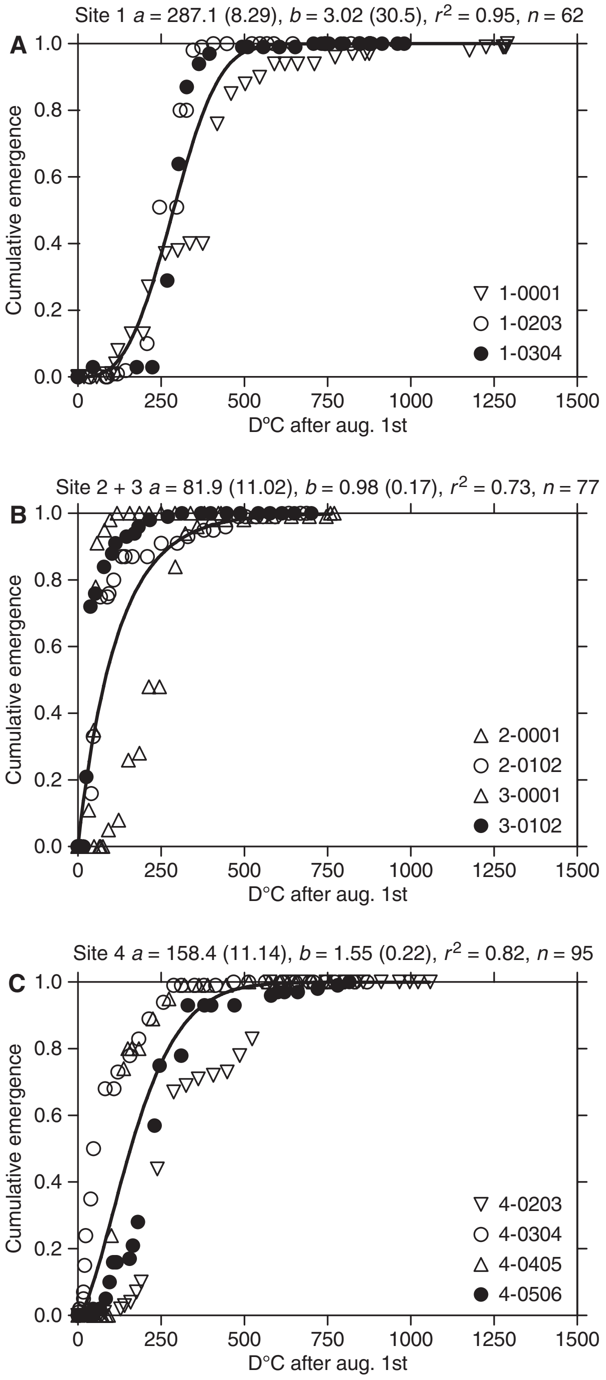

Fig. 2 Actual (symbols: see legend for years) and predicted (▬) cumulative emergence in d°C after 1 August for *Digitaria sanguinalis* in sites 1–4. Black dotted points are data for model validation.

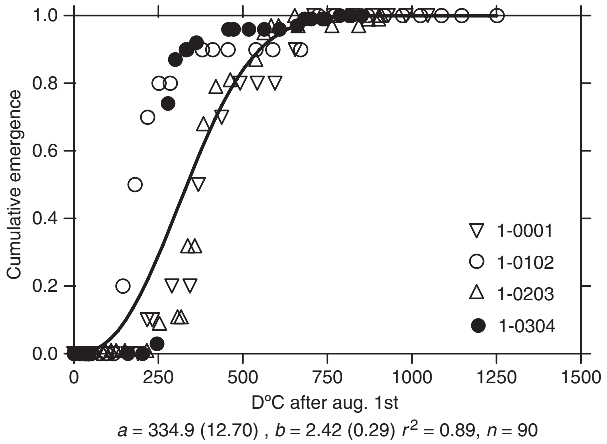

Fig. 3 Actual (symbols: see legend for years) and predicted (▬) cumulative emergence in d°C after 1 August for *Echinochloa colonum* in site 1. Black dotted points are data for model validation.

observed in the different sites. Within each site, no large variations were found among the results obtained in the various years, with good fits of all the curves (Fig. 2). The emergence process of *E. colonum* was slower, requiring 330 d°C to reach 50% emergence (Table 4). The good fit of the Weibull model indicates that the data from the 4 years were relatively uniform (Fig. 3). In the case of *E. indica*, the emergence process was almost continuous during most of the growing cycle, with 420–580 d°C required to reach 50% emergence (Table 4). The two curves fitted to the data of the two sites indicate that no large variations were found among the results obtained in the various years (Fig. 4). *Setaria geniculata* was an early emerger in the three sites where it was present, requiring 150–200 d°C to reach 50% emergence (Table 4). As in the previous cases, a single model was fitted to the data from the four experimental years in each site (Fig. 5). The emergence response of *S. halepense* to thermal time was also different in the various sites. In sites 1–3, the process was relatively fast, with 270–290 d°C required to reach 50% emergence (Table 4 and Fig. 6). In contrast, in site 4 there was an almost continuous emergence with 500 d°C required for 50% emergence. The only two data sets available for *U. platyphylla* indicate that this species has an early emergence, with 100 d°C required for 50% emergence (Table 4 and Fig. 7).

Model validation (Table 5) showed high correlation among observed and predicted values, with the coefficients of determination ranging from 0.71 to 0.98.

Discussion

Although we intended to find a single model that could fit the data from each species, considerable variation was observed among the data from the four sites. The only data sets that yielded similar models were those from sites 2 and 3. These two sites have similar soils and similar climate. Consequently, the algorithms in WeedCast calculated similar patterns of soil temperature (Fig. 8) using the daily air temperature as the main input. In contrast, although sites 1 and 4 have similar soil characteristics, the patterns of soil temperature were clearly different (Fig. 8). Although this difference may be due in

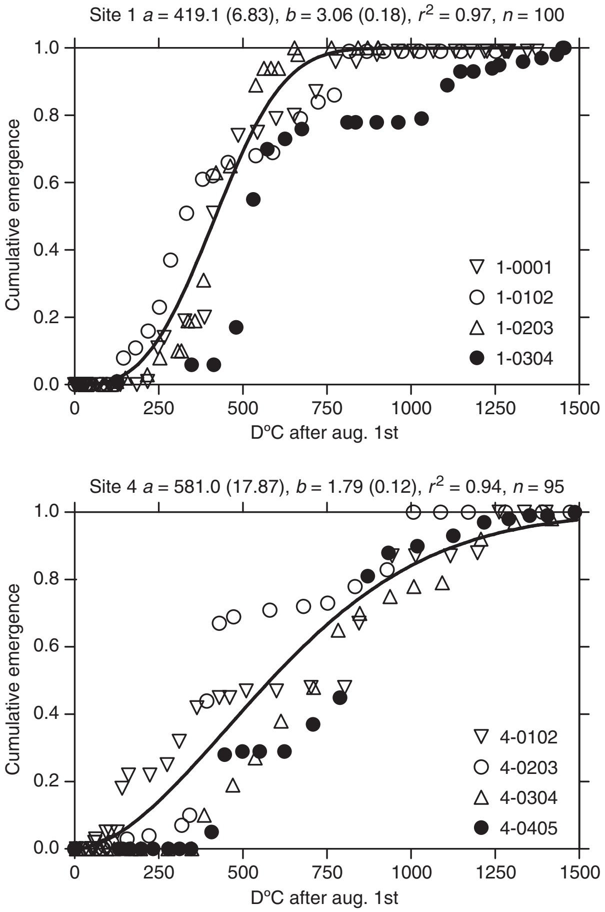

Fig. 4 Actual (symbols: see legend for years) and predicted (▬) cumulative emergence in d°C after 1 August for *Eleusine indica* in sites 1 and 4. Black dotted points are data for model validation.

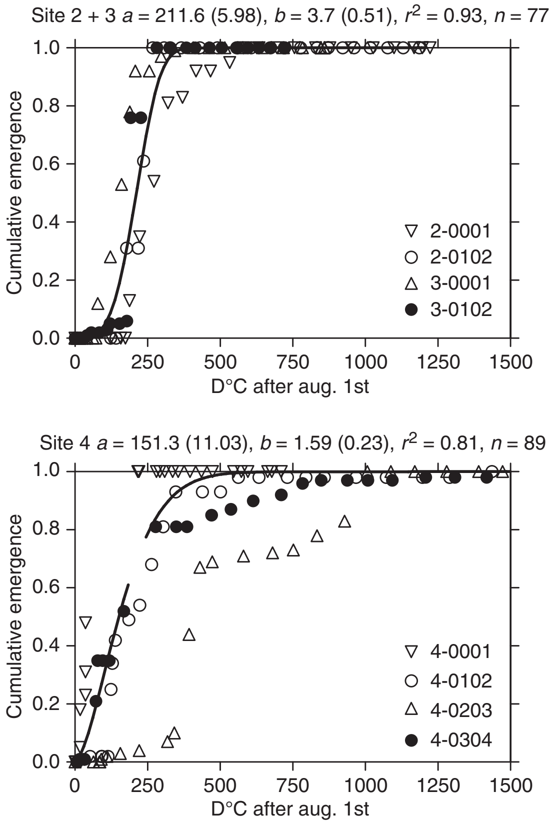

Fig. 5 Actual (symbols: see legend for years) and predicted (▬) cumulative emergence in d°C after 1 August for *Setaria geniculata* in sites 2–4. Black dotted points are data for model validation.

part to differences in the temperature patterns of the two sites (site 4 is closer to the River Plate and with a milder climate) it is possible that WeedCast temperature estimations were not very precise. These two sites had more than 5 years of direct drilling at the onset of the experiment and heavy crop residues accumulated on the soil surface. Although the WeedCast model includes an option ('previous crops') that takes into consideration the volume of crop residues left on the soil surface by the precedent crops, the 'age' of the system under direct drilling is not taken into account. It is presumed that, under no tillage systems, the increase of crop residues year after year is a factor that may be responsible for ample variations in the temperature of the upper soil layer. This factor is not considered in the current version of this program.

Based on the results of these experiments we may classify the six species into three emergence-span groups. *Eleusine indica, U. platyphylla* and *E. colonum* were the species with the longest period of emergence, completing the emergence process in 940–1660 d°C. The intermediate emergence group (*D. sanguinalis* and *S. halepense*) completed the emergence process in 540–1090 d°C. *Setaria geniculata* presented the shortest emergence period, requiring 290–660 d°C to complete this process.

The emergence period varied not only among species but also among sites. This period was always longer in site 4 than in site 1, with sites 2 and 3 having an intermediate duration. This feature may be attributed to the dynamics of dormancy release in each site. According to Finch-Savage and Leubner-Metzger (2006), dormancy is a moving target continuously reacting to the environment and adjusting the conditions required for germination. Induction and breaking of shallow dormancy in variable environments are gradual processes where the temperature range permissive for germination and/or the sensitivity to other factors widens or narrows continuously. Once the dormancy breaking process ends, germination progresses at different rates according to the ambient conditions. These rates are a function of the difference between ambient conditions and a germination threshold. In such a way, soil temperature and temperature amplitude could be acting together to produce the patterns observed. Following this reasoning, a possible explanation for the more extended emergence period of site 4, in comparison with the other three sites, may be found in the dynamics of soil temperature and air temperature amplitude (Fig. 8). During the period when

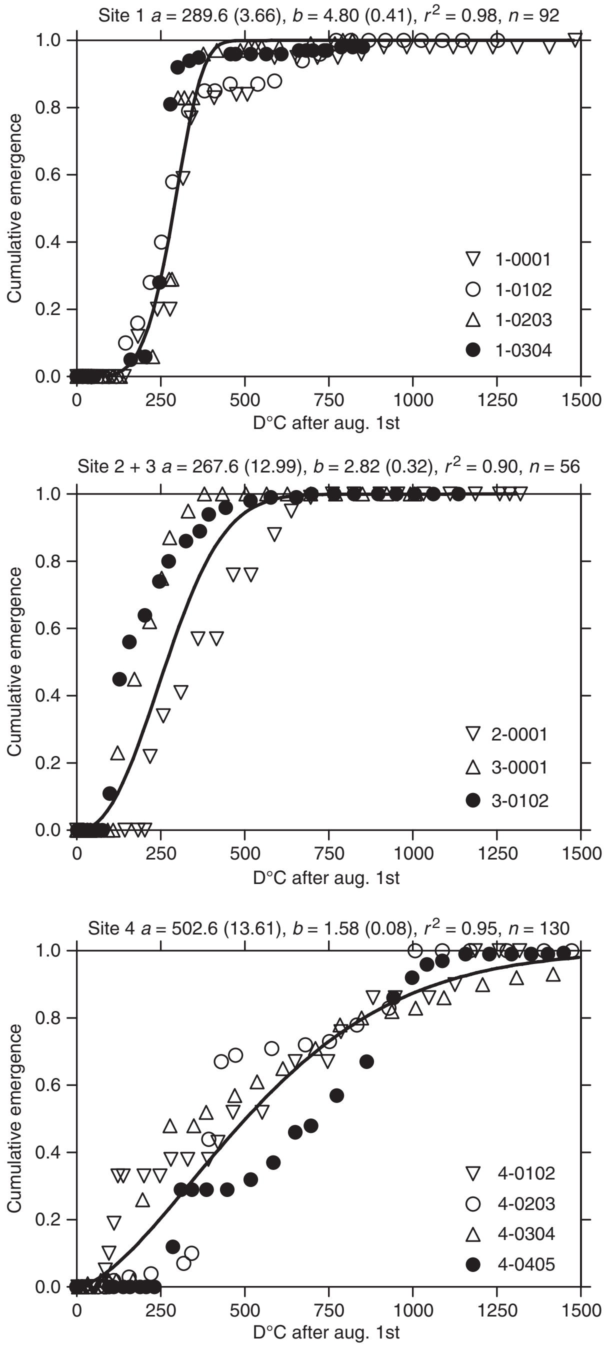

Fig. 6 Actual (symbols: see legend for years) and predicted (▬) cumulative emergence in d°C after 1 August for *Sorghum halepense* in sites 1–4. Black dotted points are data for model validation.

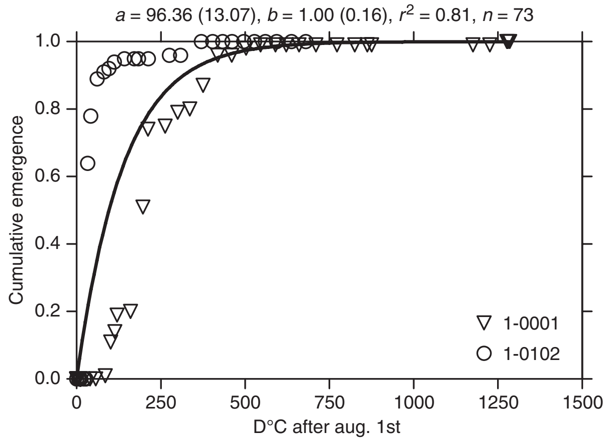

Fig. 7 Actual (symbols: see legend for years) and predicted (▬) cumulative emergence in d°C after 1 August for *Urochloa platyphylla* in site 1.

Table 5 Quality of predicted/observed linear regression for each species fitting eqn 3 to values calculated by eqn. 2 models for each species/location: significance of intercept departure from zero, parameter b (slope) of the eqn (3) does not significantly depart from 1

		Eqn. 2 model		
Species	Site	Intercept	Slope	R^2
Digitaria sanguinalis	1	NS	NS	0.93
	2 & 3	NS	NS	0.89
	4	NS	NS	0.87
Echinochloa colonum	1	NS	NS	0.88
Eleusine indica	1	NS	NS	0.71
	4	NS	NS	0.88
Setaria geniculata	2 & 3	NS	NS	0.93
	4	NS	NS	0.98
Sorghum halepense	1	NS	NS	0.90
	2 & 3	NS	NS	0.92
	4	NS	NS	0.89
Urochloa platyphylla	–	–	–	–

dormancy was overcome and more that 50% of total emergence occurred (120 DAA), daily amplitudes of air temperature were – on the average – 14.7, 12.9 and 12.4°C for sites 1–4 respectively. In the same period, calculated soil temperatures at 2 cm depth were 10.8, 10.3 and 8°C in sites 1–4 respectively. The hypothesis could be more closely examined by comparing the models of *S. halepense* in the three sites (Fig. 6). We selected this species because it was present in the four sites, the amount of data was consistent, and the goodness of fit of the models and the coefficient of determination of model validations were very high (Table 4). In site 1, soil temperature first reached the T_b (8.5°C) 20 DAA and clearly overcame this threshold from 40 DAA onwards. In sites 2 and 3, soil temperature reached the T_b after 35 DAA and clearly overcame it from 45 DAA onwards. In contrast, in site 4, soil temperature did not consistently reach the T_b until 60 DAA. These results are in concordance with those obtained experimentally by Benech-Arnold *et al.* (1990a) and Benech-Arnold *et al.* (1990b). These authors found that *S. halepense* seeds in the soil begin to accumulate thermal time once they pass through pulses of different requirements (number of cycles of alternating soil temperature and soil temperature below a maximum,

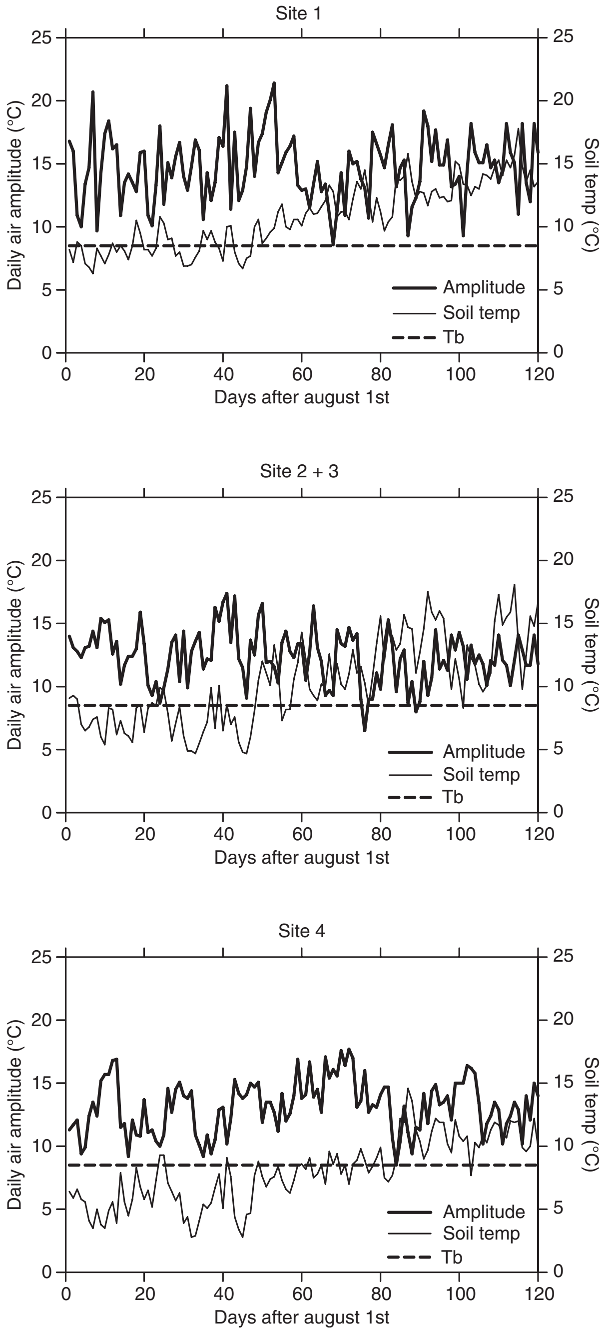

Fig. 8 Air temperature amplitude and soil temperature at sites 1–4.

e.g. four cycles of 12°C). Early works on seed longevity and seedling emergence under field conditions also revealed that seeds of *S. halepense* have a cyclic pattern of dormancy–dormancy release (Leguizamón, 1986). The response to alternate cycles has also recently been found in *Phragmites australis*. In this species, the speed of the germination process increases as the temperature amplitude increases over the T_b (Ekstam *et al.*, 1999).

A further source of variation may be the different environmental requirements and physiological responses of local ecotypes (Probert, 1992; Forcella *et al.*, 2000). This type of response has been reported for *Setaria glauca* (Baskin *et al.*, 1996). In the case of *E. indica,* freshly shed seeds may be dormant and require light or scarification to induce germination (Kanzler & van Staden, 1984). Older seeds have shallow dormancy and germination may be enhanced by alternating temperature and other factors (Chin & Raja Harun, 1979).

Bearing in mind what has been stated above, a further step would be to improve the models adding more data sets obtained in different areas and extending the WeedCast model to predict more accurately the temperature of soils covered with crop residues (an increasingly frequent situation). This may be the most straight-forward way to adjust models of general application for different areas. Meanwhile, models as presented here can be used for specific sites.

In the case of early emerging species with a short 'emergence window', such as *S. geniculata,* the use of post-emergence non-residual herbicides may be the most appropriate control strategy. In the case of late emerging species with a medium to long emergence window, such as *D. sanguinalis, E. indica, S. halepense* and *E. colonum*, the chemical control strategy should be based on the use of residual herbicides, possibly combined with post-emergence ones. In any case, the capability of predicting the onset and the time-span of seedling emergence is a powerful tool to optimise the schedule for herbicide spraying operations. From the point of view of crop-weed interactions, the duration of the emergence period may have important consequences for the duration of the competitive period. Using this knowledge to refine weed control tactics is of major importance to avoid a build up of the weed seedbank.

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