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SHORT COMMUNICATION

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A predictive model for the time course of seedling emergence of *Phalaris brachystachys* (short-spiked canary grass) in wheat fields

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Abstract

Aim of study: A predictive model of the seedling emergence pattern of *Phalaris brachystachys* Link (short-spiked canary grass) was developed, aimed to contribute to support a more efficient management of this troublesome, competitive weed in winter cereal crops around its native Mediterranean range and in different areas of the world where it is introduced.

Area of study: Southern (Andalusia) and northern Spain (Navarra).

Material and methods: A model describing the emergence pattern of *P. brachystachys* in cereal fields based on accumulation of hydrothermal time in soil was developed and validated. For model development, cumulative emergence data were obtained in an experimental field, while an independent validation of the model was conducted with data collected in two commercial wheat fields from climatically contrasting regions of Spain.

Main results: The relationship between cumulative emergence and cumulative hydrothermal time (CHT) was well described by a Logistic model. According to model predictions, 50% and 95% seedling emergence takes place at 108 and 160 CHT above base water potential for seed germination, respectively. The model accurately predicted the seedling emergence time course of P. brachystachys in the two commercial wheat fields ($R^2 \geq 0.92$).

Research highlights: This model is a new tool that may be useful to improve the timing of control measures to maximize efficiency in reducing *P. brachystachys* infestations in cereal crops.

Additional keywords: hydrothermal time; Logistic model; model validation; weed management

Abbreviations used: CHT (cumulative hydrothermal time); EU (European Union); HT (hydrothermal time); RMSE (root mean square error); SARES (sum of absolute residuals); SRES (sum of residuals)

Authors' contributions: FB performed the experiments, contributed to conceptualization and methodology. JAL performed the experiments. JLGA contributed to conceptualization, methodology, formal analysis, obtaining funds and supervision. Wrote the paper: FB and JLGA. All authors read and approved the final manuscript.

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Introduction

The annual Poaceae species *Phalaris brachystachys* Link (short-spiked canary grass) is considered to be a troublesome weed of winter cereals fields with clay-rich soils both in its native area around the Mediterranean basin and in parts of Europe, North-America and Australasia where it is introduced (Jimenez-Hidalgo *et al.*, 1997; Gonzalez-Andujar & Saavedra, 2003; Waheed *et al.*, 2009). This weed is very prolific (Gonzalez-Andujar *et al.*, 2005) and is competitive with winter cereal plants, reducing crop yields up to 60% (Cudney & Hill, 1979; Afentouli & Eleftherohorinos, 1996, 1999; Jimenez-Hidalgo *et al.*, 1997).

Control measures of *P. brachystachys* populations in cereal fields are mainly based on herbicides (Gonzalez-Diaz *et al.*, 2009; Zambrano-Navea *et al.*, 2012), but this option results in a marked increase in annual costs of crop production and an increased risk of development of herbicide resistance. *P. brachystachys* has developed resistance to ACCase inhibitors (Golmohammadzadeh *et al.*, 2020).

In the European Union (EU), the ongoing review process of pesticides, started a decade ago to increase their sustainable use, has currently led to a reduced number of selective products available for chemical weed control. As a result, there is a great emphasis on improve herbicide application timing. Predictive weed emergence models can serve as the basis for the development of decision-making tools (*e.g.* Masin *et al.*, 2014). Nonlinear thermal and hydrothermal models of seedling emergence are so far the most widely used approaches for practical weed emergence predictions (Gonzalez-Andujar *et al.*, 2016a). They are based on the thermal or hydrothermal-time concept proposed by Gummerson (1986), which assume that seeds need to accumulate a certain amount of growing degree days, either independent of water availability in soil (thermal models) or only when water availability is permissive for germination (hydrothermal models), before completing seed germination and seedling emergence. These models have been fitted to a range of weed species of Mediterranean crops, including *Galium* spp. (Royo-Esnal *et al.*, 2012), *Lolium rigidum* (Izquierdo *et al.*, 2013) and *Conyza bonariensis* (Zambrano-Navea *et al.*, 2013). To the best of our knowledge, no emergence model has yet been developed for *P. brachystachys* that can provide precise information to farmers to increase efficacy of currently available control measures. Because of the negative impact of *P. brachystachys* on cereal yields and the need to decrease the selection pressure for herbicide resistance, the present study aimed to develop and validate a predictive model of the pattern of emergence of this weed species in Mediterranean winter cereal fields as a function of soil temperature and water potential.

Material and methods

The study consisted of two experimental works. The first experiment, based on sown plots, was aimed to develop the model. The second one, performed in two commercial cereal fields located in climatically contrasting North and South Spain, was intended to validate it.

Experiment in sown plots: model development

A controlled experiment was conducted in an experimental field at La Rábida Campus of the University of Huelva, in Huelva Province, Andalusia, south-western Spain (37º12′10"N, 6º55′05"W). Mature caryopses of *P. brachystachys* (hereafter seeds) were collected in June 2006 from a wheat field near Huelva, and stored in airtight containers at 4°C until needed. Ten 25 × 25 cm plots were randomly established and the soil up to 5 cm deep was replaced by a substrate. The substrate was a mixture of 50% Kekkilä garden peat, 25% sand, and 25% local sandy clay soil. After autoclave sterilization to suppress viability of existing seeds, the volume of substrate to be added to each plot was thoroughly mixed with 200 seeds of *P. brachystachys* and placed on topsoil on 27th November 2007. Seed losses to soil surface-foraging predators were prevented by placing 2-mm mesh nets over 0.4 m diameter, 0.1 m height PVC fences placed encircling the plots. An additional, similarly arranged plot with substrate lacking seeds was established to support sensors connected to a datalogger set to record at hourly intervals temperature (Hobo TMC6-HD, Onset Computer Corp., USA) and electrical conductivity (Hobo EC-20, 20-cm length blade) at 5 cm depth. Numbers of emerged seedlings were recorded and thereafter removed at weekly intervals, from sowing until end of seedling emergence (mid-April).

Experiments in commercial cereal fields: model validation

Seedling emergence was monitored in two climatically contrasting commercial wheat fields with clay-rich soils located c. 780 km apart, in South and North Spain. The southern field (durum wheat cv. 'Amilcar'), was located in Huelva (37º 18' N, 6º 55'W; 17 m a.s.l.) and sampled in the 2007-2008 season. The climate is typically Mediterranean, with a mean annual temperature of 16.6 °C and mean annual rainfall of 555 mm, mainly distributed between October and April. The crop season of winter cereals in the southern area encompasses from late November-early December (crop sowing) to late May-June (crop harvest). The northern field (bread wheat cv. 'Berdun') was located in Arazuri, Navarra, (42º 49' N, 1º 43' W; 395 m a.s.l.) and sampled in the 2006-2007 season. The climate is temperate with cool summers with abundant rainfall. The mean annual temperature is 12.3 °C and the mean annual rainfall is 750 mm. In this area cereal sowing takes place in October and harvest occurs in July. In both fields, emergence data were collected weekly, from crop sowing until the end of seedling emergence by mid-April, from 20 randomly distributed 50 × 50 cm permanent quadrats.

The calculation of hydrothermal time

Climatic variables were obtained from meteorological stations located less than 10 km from the commercial fields. Soil temperature (T; ºC) and water potential (ψ; MPa) at 5 cm depth were estimated using the STM^2 software (Spokas & Forcella, 2009) and used to calculate the HT accumulated in soil in day t, HT(t), using the following equation (Schutte *et al.*, 2008):

$$HT(t) = H(t) \cdot T(t) \qquad [1]$$

H(t) = 1 when the actual water potential at day t, $\psi(t)$, is larger than or equal to the base water potential (ψ_b), *i.e.* the highest value of soil water potential that prevents germination of *P. brachystachys* seeds, otherwise $H(t)$ = 0, and

$$T(t) = max\{T(t) -^{o} T_b, 0\} \qquad [2]$$

where T(t) is the average soil temperature at day t and T_b the base temperature for seed germination. Cumulative hydrothermal time (*CHT*) starting at crop sowing up to day n is defined as follows:

$$CHT\,(n) = \sum_{t=1}^{n} HT(t) \qquad [3]$$

For *P. brachystachy*s, Tb = 0.8 °C and ψ_b =−1.50 MPa (M. J. Sánchez del Arco, *pers. comm.*).

Model development and evaluation

Cumulative seedling emergence (C) in response to *CHT* was modeled by the Logistic function (Gonzalez-Andujar *et al.*, 2016a),

$$C = K/(1 + \exp(-b(CHT - M))) \qquad [4]$$

where K is the maximum emergence predicted by the model, b is the rate of increase in the emergence, M is cumulative HT at the point of inflection (50% emergence).

Model performance was assessed by calculating the root mean-square error (RMSE), sum of the residuals (SRES) and sum of the absolute residuals (SARES). In conjunction, they are useful measures for estimating variation and bias in a model. These measures are defined by the following equations:

$$RMSE = \sqrt{(1/n)\sum_{i=1}^{n}(x_i - y_i)^2} \qquad [5]$$

$$SRES = \sum_{i=1}^{n}(x_i - y_i) \qquad [6]$$

$$SARES = \sum_{i=1}^{n} ABS\,(x_i - y_i) \qquad [7]$$

where x_i and y_i represent observed and predicted cumulative percentage seedling emergence, respectively; ABS is absolute value of the number within parentheses and n is the number of observations. A small RMSE value suggests close agreement between simulated and observed values. The SRES and SARES expressions are useful in determining how errors in the model cancel out. If SRES is small compared to SARES, errors in the model will tend to cancel out. If SRES and SARES are large and SRES is positive, the model tends to underestimate the observed value. However, if SRES is negative and large in comparison to SARES then the model will tend to overestimate the observed value. Model parameters were estimated by nonlinear least-squares regression using the Marquard-Levenberg algorithm in SigmaPlot v.11 (Systat Software, Inc). Multiple initial values were used to ensure that the solution was global rather than local.

For model validation, we compared the models' estimates of cumulative emergence against the independent data set obtained in the experiments under commercial field conditions. Prediction accuracy was evaluated by the coefficient of determination (R^2) of the linear regression of predicted against observed cumulative seedling emergence.

Results and discussion

The Logistic model provided a good fit of the field data and was accurate enough in explaining cumulative emergence as a function of HT (Fig. 1). The RMSE of the model in predicting seedling emergence was quite low (1.33), and SRES (0.0026) was small compared to SARES (39.17), suggesting there was no bias in the model. Parameter estimates (mean ± standard error) were K= 98.18 ± 1.37, b= 0.062 ± 0.0070 and M= 108.20 ± 1.82. According to model predictions, 50% and 95% seedling emergence takes place at 108 and 160 *CHT*, respectively (Fig. 1).

The time course of *Ph. brachystachys* seedling emergence predicted by the model showed a good correspondence with observed values in commercial wheat

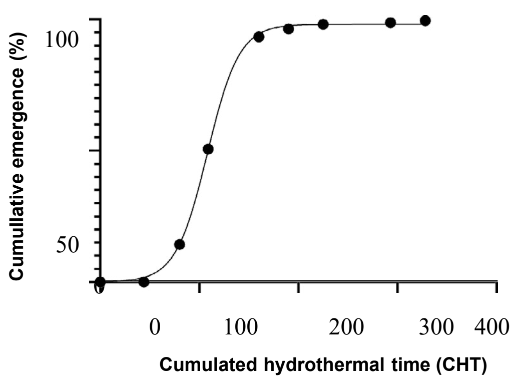

Figure 1. Observed (dots) and predicted (solid line) cumulative emergence (%) of *P. brachystachys* as a function of cumulative hydrothermal time. Predictions results from the fitted Logistic model to the experimental data set (see text for details)

fields, both in Huelva ($R^2 = 0.98$) and Aruzari ($R^2 = 0.92$) (Fig. 2).

In recent years, the EU has introduced increasingly stringent regulations on the use of pesticides. As a consequence, farmers are putting increased emphasis on the improvement of the application timing of herbicides as a way to optimize control efficiency. This goal can be accomplished with the aid of efficient predictive models of weed emergence which, in turn, could serve as the basis for the development of decision support systems to help farmers in making weed control decisions (Masin *et al.*, 2014; Gonzalez-Andujar, 2020). In our study, the HT Logistic model developed offers a good fit and unbiased description of *P. brachystachys* seedlings emergence in wheat fields. The Logistic model predicts that 50% and 95% emergence is reached at 108 *CHT* and 169 *CHT*, respectively, indicating a rapid establishment of the population following crop sowing (Hidalgo *et al.*, 1990). A similar pattern was modeled by Gonzalez-Andujar *et al.* (2016b) for the co-occurring, co-generic grass weed *Phalaris paradoxa.* In plants, competitive advantage can be gained through earlier emergence (Dubois & Cheptou, 2012) and, in fact, many authors have reported that the magnitude of yield losses in annual crops due to weed competition depends on the timing of emergence of weed seedlings relative to the crops' (*e.g.* Chikoye *et al.*, 1995; Knezevic *et al.*, 1997). In addition, more advanced phenological stages of weeds at application time are generally associated to lower treatment effectiveness (*e.g.* Fernández-Moreno *et al.*, 2017) and thus increased yield losses (Zambrano-Navea *et al.*, 2012; Alcantara *et al.*, 2017). Therefore, adjustment of application timing appears to be a key factor to effectively control this weed.

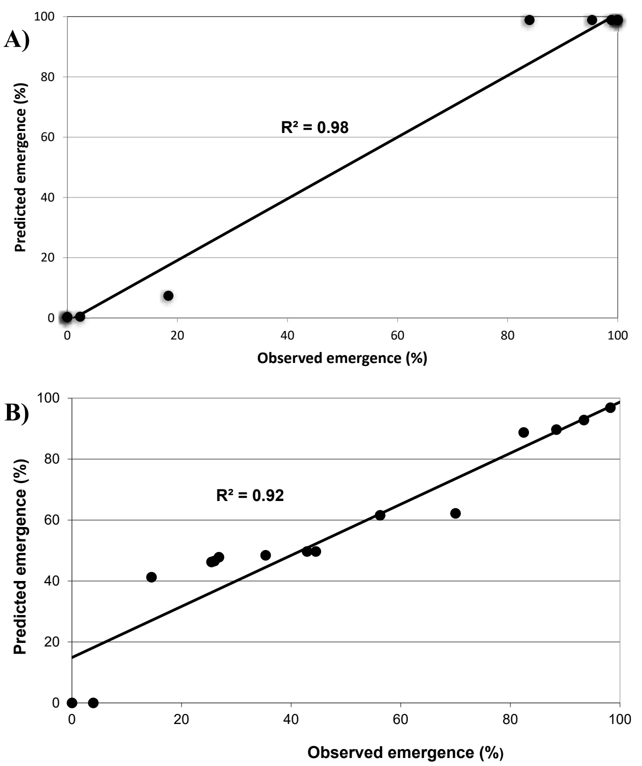

Figure 2. Validation of the Logistic emergence model for *Phalaris brachystachys* in wheat fields. A) Huelva; B) Aruzari (see text for details).

The proposed emergence model showed an excellent agreement with the observed seedling emergence patterns in the validation experiments in the two climatically contrasting commercial fields. This ability to accurately predict the seedling emergence pattern under two very different environmental conditions is a positive feature of this model (Egea-Cobero *et al.*, 2020).

In conclusion, the hydrothermal model proposed appears to be robust enough to be tested as a predictive tool of *P. brachystachys* emergence time course in winter cereal fields. Further research should be addressed for a wider validation of the model (Loddo *et al.*, 2018; Egea-Cobrero *et al.*, 2020) that can render it a valuable tool for farmers for adequate timing of control measures of *P. brachystachys*. Studies conducted in different and widely dispersed locations would be useful to assess the general model validation. Furthermore, integrated into a decision support system (Gonzalez-Andujar, 2020), the model may contribute to the sustainability of weed management in dryland cereal fields.

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