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Predicting Seedling Emergence of Three Canarygrass (*Phalaris*) Species under Semi-Arid Conditions Using Parametric and Non-Parametric Models

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Abstract: The *Phalaris* genus includes annual weed species such as short-spiked canarygrass (*Phalaris brachystachys* Link.), little-seed canarygrass (*Phalaris minor* Retz.) and hood canarygrass (*Phalaris paradoxa* L.), which are especially problematic in Spain; as such, there is a need to develop models to predict the timing of their emergence. Field experiments were conducted at two different locations during two (2006/07 and 2007/08) and three (from 2005/06 to 2007/08) growing seasons. In both locations, 500 seeds of each Phalaris species were sown each growing season, simulating rain-fed cereal field conditions. In addition, the models were validated with three, four and eight independent experiments for *P. brachystachys*, *P. minor* and *P. paradoxa*, respectively. The emergence period of the three Phalaris species lasted between 31 and 48 days after sowing (DAS), showing two main flushes. The three cardinal points for parametric and non-parametric models were established to be between −1 °C and 1 °C for base temperature, between 9.8 °C and 11.8 °C for optimal temperature and between 21.2 °C and 23.4 °C for ceiling temperature; base water potential was estimated to be between −1 and −1.1 MPa. Both parametric and non-parametric models obtained similar results and were successfully validated in 12 out of 15 independent experiments.

Keywords: hydrothermal time; modeling; *Phalaris brachystachys*; *Phalaris minor*; *Phalaris paradoxa*; weed emergence model

1. Introduction

Phalaris is a grass genus that includes annual weed species that are spread through the Mediterranean basin area [1,2], India [3,4], China [5] and the United States [6]. Similar to many problematic annual weeds, the success of this genus as a weed can be attributed to its high seed production, and hence, high rate of population growth [7].

In Spain, there are three *Phalaris* weed species: short-spiked canarygrass (*Phalaris brachystachys* Link.), little-seed canarygrass (*Phalaris minor* Retz.) and hood canarygrass (*Phalaris paradoxa* L.) [1]. These weeds are highly concerning in winter cereals crops [8,9], where yields can be reduced from 16% with densities of 50 panicles m^{-2}, and up to 60% with densities of 900 plants m^{-2} [10–12]; however, these species can also be problematic in some summer crops, such as sunflower [9].

The difficulty of their chemical control and the high cost of effective herbicides against these weeds are probably the main reasons these weed species are problematic in winter cereal crops [13]. In addition, the selection of herbicide-resistant biotypes has made their control even more complicated. There have been 11 and 8 cases of herbicide-resistant biotypes of *P. minor* and *P. paradoxa* that involve 22 and 12 active ingredients, respectively, of three modes of actions (ACCase inhibitors, ALS inhibitors and Photosystem II inhibitors) described so far. Further, there are four more cases for *P. brachystachys*, belonging to eight

active ingredients of two modes of action (ACCase inhibitors and ALS inhibitors) [14]. Alcantara et al. [8] demonstrated, for the *Phalaris* species, that the efficacy of herbicides is higher when optimizing the timing of chemical control, when it is possible to reduce the number of applied herbicides, and hence, to reduce the application cost.

Understanding the pattern of weed emergence can help in the decision support system (DSS) for weed management [15], such as timing the herbicide application. Weed emergence is mainly determined by temperature, water potential, air quality and light [15], and some of these parameters have been effectively used to predict weed emergence. Thermal time (TT)-based models are the easiest to develop for weed emergence prediction as the temperature is the only considered factor, and for this reason, they have been widely used [16]. TT is the accumulation of daily thermal degrees (DTD), which are defined by three cardinal temperatures: base (T_b), optimum (T_o) and ceiling temperature (T_c). T_b is defined as the temperature at which DTD accumulation starts and increases linearly until T_o, which is the temperature at which greater DTD accumulation happens. Above T_o, DTD accumulation decreases until T_c, over which no more DTD accumulation occurs [17]. Hydrothermal time (HTT)-based models are more detailed than TT, where DTD accumulation can happen only when enough soil moisture is available, that is, when the soil water potential (Ψ) is above a base water potential (Ψ_b) [18].

Usually, TT and HTT-based models are developed with parametric non-linear regressions. At present, 113 emergence models (66 for dicot and 47 for monocots) have been developed using this procedure [16]. The success of these kinds of models relies on ease of management and practicality; however, they have some statistical limitations, mainly due to a lack of flexibility in capturing complex features [19]. Censored observations are another statistical limitation, as knowing the exact seedling emergence moment between two sampling dates is impossible; thus, alternative non-parametric regressions could be more appropriate approaches to describe weed emergence [19] and have already been developed by other authors [19,20].

Overall, models for the emergence description of the three *Phalaris* species would ease their management. In fact, a model for *P. minor* was already published [21], but this was developed under controlled conditions and only used moisture to predict germination. Many authors underline the importance of temperature in the emergence of *Phalaris* species [11,22,23]; thus, a TT or HTT model would be appropriate to describe their emergence. The aim of this work was to develop new TT and HTT-based models for each *Phalaris* species, using the two different approaches previously described, and compare their approximations to determine which would be most appropriate for future application.

2. Materials and Methods

2.1. Plant Material

In the case of *P. brachystachys* and *P. paradoxa*, seeds were harvested in June 2005 from a commercial wheat field near Jerez, Cadiz, in southern Spain (37.15 N, 6.18 W); whereas seeds of *P. minor* were collected from a commercial wheat field of Cordoba (37.86 N, 4.83 W). For the three species, seeds were collected from more than 20 individuals. Once at the laboratory, seeds were cleaned and dry-stored in a refrigerator at 4 °C until the sowing date.

2.2. Experimental Design

The experiment was carried out at two different locations, Tomejil (37.40 N, 5.58 W) and in the Higher Technical School of Agricultural Engineering of the University of Seville (ETSIA) (37.35 N, 5.93 W), during two (2006/07 and 2007/08) and three (2005/06 to 2007/08) growing seasons, respectively. The soil structure at Tomejil and ETSIA was vertisol (6% sand, 34% silt and 60% clay) and loam clay soil (39% sand, 29% silt and 32% clay), respectively.

In both locations, four quadrates of 25 × 25 cm were sown with 500 seeds for each *Phalaris* species and each growing season. The sowing procedure varied between locations.

In Tomejil, commercial field soil was used without any previous replacement or sterilization. In this location, the upper 2 cm of soil layer was extracted, mixed with the corresponding seeds and then returned to the ground so that the seeds were evenly distributed in the top 2 cm of the soil. An additional control was introduced next to each plot to avoid the natural seed bank effect. In contrast, in the ETSIA experiments, the top 5 cm of soil was replaced by a mixture of 25% Kekkilä peat (Kekkilä Oy, Vantaa, Finland), 25% sand and 50% local soil. This mixture was oven-dried at 100 °C for 22 h to sterilize from pathogens and natural seed banks. Afterward, seeds were added to this mixture and were incorporated into the corresponding plot. In both locations, the date when the seeds were mixed with the soil was considered the sowing day. This procedure was followed each year and each newly sowed plot was placed next to that from the previous season, which was left undisturbed. This procedure allowed us to monitor seedling emergence over two growing seasons and to study the emergence under a tillage simulation (sowing season), in which the TT and HTT accumulation starting from the sowing date, and under non-tillage situation (second season), in which the initial moment was chosen at the first relevant rainfall. As a result, the models could be tested in eight different situations (Table 1).

Table 1. Sowing locations and codes, sowing dates, dates of the first relevant precipitation and the total number of emergences for each Phalaris species, considering the three repetitions together. PHABR, *P. brachystachys*; PHAMI, *P. minor*; PHAPA, *P. paradoxa*.

Location	Code [1]	Sowing Date	First Relevant Rain	Total Emergence		
				PHABR	PHAMI	PHAPA
ETSIA	S06YR06	11 November 2005	14 November 2005	1794	44	1519
ETSIA	S06YR07		13 September 2006	43	32	174
ETSIA	S07YR07	12 November 2006	16 November 2006	1391	62	914
ETSIA	S07YR08		21 September 2007	46	38	178
ETSIA	S08YR08	15 November 2007	20 November 2007	95	66	895
Tomejil	S07YR07	15 November 2006	16 November 2006	55	90	473
Tomejil	S07YR08		21 September 2007	-	-	36
Tomejil	S08YR08	20 November 2007	22 November 2007	190	58	679

[1] The sowing code represents the year when sowing was performed and the year when the emergence was monitored, i.e., both S06YR06 and S06YR07 are the same plot that was sown in 2005/06, but the first code represents the emergence results from the same season (2005/06), whereas the second is showing results from the second season (2006/07).

Seedling emergence was recorded weekly with destructive counts to avoid double counts, between October and May each season. A 2 mm mesh cage was placed over each plot to avoid seed or seedling losses by predators.

2.3. Estimation of TT and HTT

Three biological parameters, T_b, T_o and T_c, were used to estimate TT [24,25]. For the estimation of HTT, the accumulation of TT was only produced when soil moisture (soil water potential, Ψ) rose above a base water potential (Ψ_b). TT and HTT are the accumulated DTD and hydrothermal degrees (DHD), which were obtained via the following:

$$\text{If } T_b > T < T_o: \text{DTD} = (T - T_b)/(T_o - T_b)$$

$$\text{If } T_o > T < T_c: \text{DTD} = (T_o - T_b)/(T_c - T_o) * (T_c - T)/(T_o - T_b)$$

$$\text{If } T < T_b \text{ or } T > T_c: \text{DTD} = 0$$

$$\text{If } \Psi < \Psi_b: \text{DHD} = 0$$

$$\text{If } \Psi > \Psi_b: \text{DHD} = \text{DTD}$$

where T is the daily temperature, T_b is the base temperature, T_o is the optimal temperature, T_c is the ceiling temperature, Ψ is the daily water potential and Ψ_b is the base water potential.

The three biological parameters of TT for each species were established through an iterative process until the best combinations were obtained for the most accurate models. This best combination was chosen by representing field emergence percentages against the different TT, then applying parametric and non-parametric regressions. The same procedure was used to set the biological parameters for HTT; however, in this case, we added Ψ_b to the combination.

Daily maximum and minimum air temperatures and daily precipitation were obtained from the closest meteorological station in each location. In order to estimate the soil Ψ, Saxton and Rawls [26] equations were followed. We also used a procedure defined by Fuentes-Yagüe and García-Legaspi [27] to estimate the soil water content needed for these equations.

2.4. Development of the Parametric Model

The Weibull three parameters in Equation (1) were tested as a biological growth model in a parametric non-linear regression.

$$Y = A \left\{ 1 - e^{[-e^{(-k)} x^b]} \right\} \tag{1}$$

where Y is the cumulative emergence percentage from the total percentage of seedling emergence (A), which in this case was fixed to 100% each season, x is the TT or HTT and k is the slope of the curve at b, which is the inflection point.

2.5. Development of the Non-Parametric Model

For the non-parametric regression, observed data were aggregated using the next cumulated kernel density estimation (2) [19]:

$$F(x) = \sum_{i=1}^{n} W_i \, K(t) \left(\frac{x - t_i}{h} \right) \tag{2}$$

where $K(t)$ is the integrated Gaussian kernel (3), t_i is the TT or HTT at the middle of two consecutive inspections, W_i is the percentage of emerged seedlings counted between two consecutive inspections and h is the bandwidth or the smoother parameter.

$$K(t) = \frac{1}{\sqrt{2\pi}} e^{-t^2/2} \tag{3}$$

The bandwidth (h) was selected using the plug-in approach. This approach was conducted with the R software, using the function "hpi.kcde" from the "ks" package [28]. Then, the "kcde" function from the same package was used to apply the Gaussian kernel distribution explained before.

2.6. Model Accuracy

The accuracy of the models was tested with the root mean square error (RMSE, 4), where greater model accuracy, and thus the best combination of biological parameters, is indicated by lower RMSE values. As a reference, RMSE was evaluated with the scale proposed by Royo-Esnal et al. [29] for percentages of emergence; their model is as follows: excellent accuracy for values under 5, very good for values between 5 and 10, good for values between 10 and 15 and not successful for values over 15.

$$RMSE = \sqrt{1/n \sum_{i=0}^{n} (x_i - y_i)^2} \tag{4}$$

where x_i represents the observed cumulative percentage emergence, y_i is the predicted cumulative percentage of emergence and n is the number of observations.

2.7. Data Validation

The developed models were tested with independent data obtained from two locations (Table 2), Seville-Garden and ETSIA, during three (from 2016/17 to 2018/19 season) and one season (2018/19), respectively. In Seville-Garden (37.35 N, 5.93 W), the experiment was conducted using 35 L pots containing a mixture of 50% sand and 50% peat moss, while in the ETSIA (same location as the experiment), the experiment was performed in 25×25 cm^2 quadrants, as in the original experiment.

Table 2. Total emergence for the independent experiments.

Location	Year	Number of Emerged Seedling		
		P. brachystachys	*P. minor*	*P. paradoxa*
Sevilla-Garden	2016/17	12	29	-
	2017/18	-	48	16
	2018/19	17	103	-
ETSIA	2018/19	26	24	18

Data from five independent experiments for the emergence of *P. paradoxa* across Spain (Table 3) were used to validate the models. In these experiments, plots were also quadrates of 25 cm $\times$ 25 cm^2.

Table 3. Additional *P. paradoxa* experiments. Location, soil texture and total emerged seedling.

Location	Latitude	Longitude	Sowing Date(2019)	Sand (%)	Silt (%)	Clay (%)	Emerged Seedling
Burgos	42.4402 N	3.7209 W	Sept 18	22	46	32	369
ETSIA	37.3524 N	5.9392 W	Sept 20	38	30	32	242
Guadalcazar	37.7558 N	4.9354 W	Oct 17	36	33	30	231
Huesca	42.1277 N	0.3987 W	Oct 17	25	40	35	514
Tomejil	37.4027 N	5.5878 W	Sept 23	5	32	62	158
Valladolid	41.7789 N	4.8752 W	Oct 10	62	22	16	507

The sowing procedure for all validation experiments was the same. In each plot, the upper 2 cm of the soil layer was extracted, mixed with 1000 seeds and then returned to the ground so that the seeds were evenly distributed. Sowed seed density was between 500 and 1000; the percentage of emerged seedlings was used for validation, fixing the maximum number to 100%.

During the experiments, a temperature datalogger (digital thermometer DS18B20; Maxim, San José, CA, USA) was buried at a depth of 2 cm in each experimental location. Rainfall data were obtained from the closest meteorological station for each location.

3. Results

3.1. Weather Conditions

During the three seasons between September to May, the mean temperature was similar in both locations, ranging from 13.5 °C to 14.9 °C. September was the hottest month with a monthly mean temperature between 22.4 °C and 24.2 °C, whereas January was the coldest month (8.2–10.8 °C). On the other hand, precipitation varied in quantity and in distribution across the three seasons, ranging from 363 mm to 539 mm, with the highest recorded rainfall occurring in October, November or April, depending on the year (Table 4 and Figure 1). However, moisture was not a limiting factor that prevented seedlings from emerging in any of the three seasons.

Table 4. Average monthly temperature and total monthly precipitation at each experimental location during the experiment.

Location	Month	Temperature (°C)			Precipitation (mm)		
		2005/06	2006/07	2007/08	2005/06	2006/07	2007/08
ETSIA	September	22.4	23.7	23.0	0.0	37.0	42.8
ETSIA	October	17.7	19.6	18.8	119.2	197.8	22.6
ETSIA	November	11.5	14.3	13.1	25.4	120.6	91.4
ETSIA	December	9.7	8.9	9.6	29.0	43.4	15.0
ETSIA	January	7.1	8.2	10.8	38.0	30.4	44.8
ETSIA	February	9.1	11.8	13.4	52.8	59.6	68.4
ETSIA	March	13.4	13.4	14.1	63.6	12.4	20.0
ETSIA	April	17.0	15.3	16.8	35.2	38.0	165.4
Average		13.5	14.4	14.9	363.2	539.2	470.4
Tomejil	September		24.2	23.4		65.8	30.0
Tomejil	October		20.4	18.9		93.2	44.2
Tomejil	November		15.2	13.3		78.8	118.2
Tomejil	December		9.4	10.1		37.8	12.8
Tomejil	January		8.8	11.1		32.8	57.4
Tomejil	February		12.0	13.6		58.0	65.0
Tomejil	March		12.0	13.0		20.6	25.8
Tomejil	April		14.3	16.0		43.2	177.6
Average			14.5	14.9		430.2	531.0
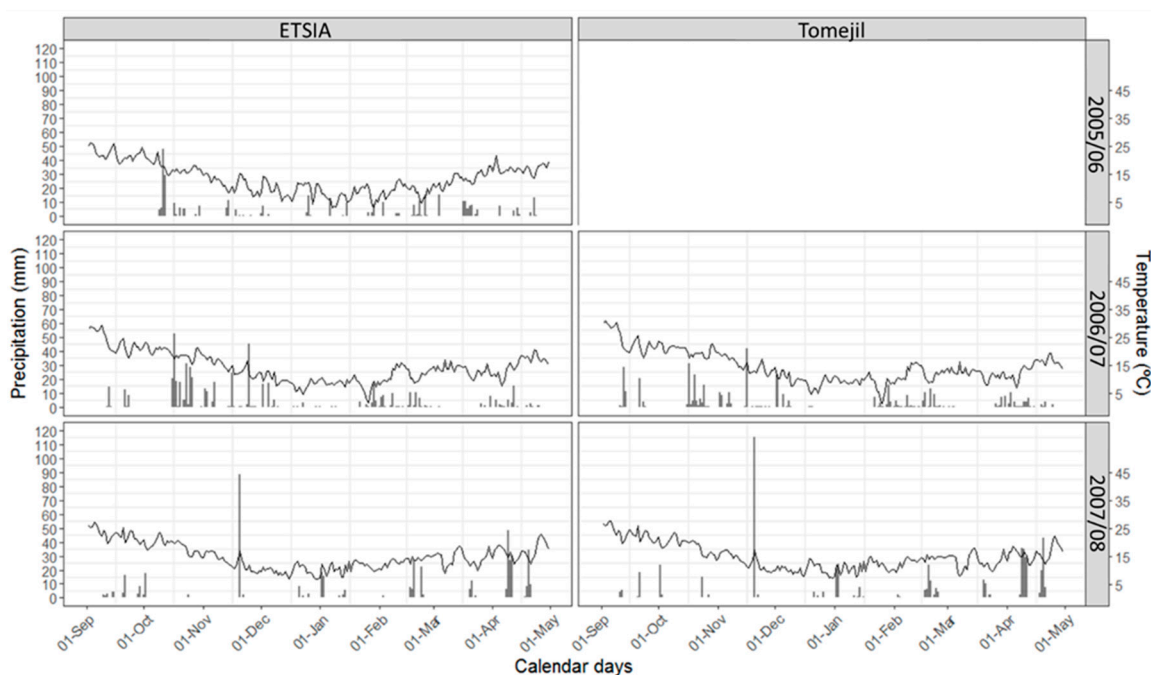
Figure 1. Daily mean air temperatures (lines) and daily precipitation (bars) at each experimental location.

3.2. Description of the Emergence

In the years in which seeds were sowed, the emergence period (time required for 10% to 90% emergence) of the three *Phalaris* species lasted between 31 and 48 days after sowing (DAS); 10% of emergence was reached between 2 and 27 December, whereas 50% and 90% were achieved between 28 December and 1 February and between 9 and 29 January, respectively. In most cases, the emergence pattern showed two flushes, the first in December and the second in February. Despite the similarity of the emergence pattern

between the three species, *P. minor* showed a longer emergence period, whereas it was shorter in *P. brachystachys* (Table 5).

Table 5. Emergence periods and dates when 50% emergence was reached in each of the three *Phalaris* species.

Location.	Sowing [1]	P. brachystachys		P. paradoxa		P. minor	
		50% [2]	Emergence [3] Period	50% [2]	Emergence [3] Period	50% [2]	Emergence [3] Period
ETSIA	S06YR06	Dec. 28	44.1	Dec. 20	59.1	Dec. 20	90.2
ETSIA	S06YR07	Nov. 30	89.9	Nov. 23	86.8	Nov. 11	88.8
ETSIA	S07YR07	Jan. 17	31.6	Jan. 07	74.9	Nov. 26	61.6
ETSIA	S07YR08	Dec. 07	88.6	Dec. 07	45.7	Mar. 18	46.7
ETSIA	S08YR08	Dec. 18	42.0	Dec. 07	16.4	Dec. 10	37.8
Tomejil	S07YR07	Feb. 01	48.0	Jan. 29	54.0	Jan. 30	61.8
Tomejil	S07YR08	-	-	Jan. 02	52.9	-	36.9
Tomejil	S08YR08	Dec. 30	30.7	Dec. 11	30.4	Dec. 30	36.9

[1] See sowing code in Table 1. [2] 50% represents when 50% emergence was reached. [3] Emergence period represents the difference in days between the dates when 10% and 90% emergence was reached.

Seeds that did not emerge during the first season and remained in the soil began emergence earlier in the following season due to the rainfall during October. In 2006/07, 50% emergence was reached during December, but 90% emergence occurred in February; thus, the emergence period was approximately three months. On the contrary, during 2007/08, the emergence period was similar or even shorter than that in newly sowed plots, except for *P. brachystachys*, which showed similar behavior to the previous season (Figure 2 and Table 5).
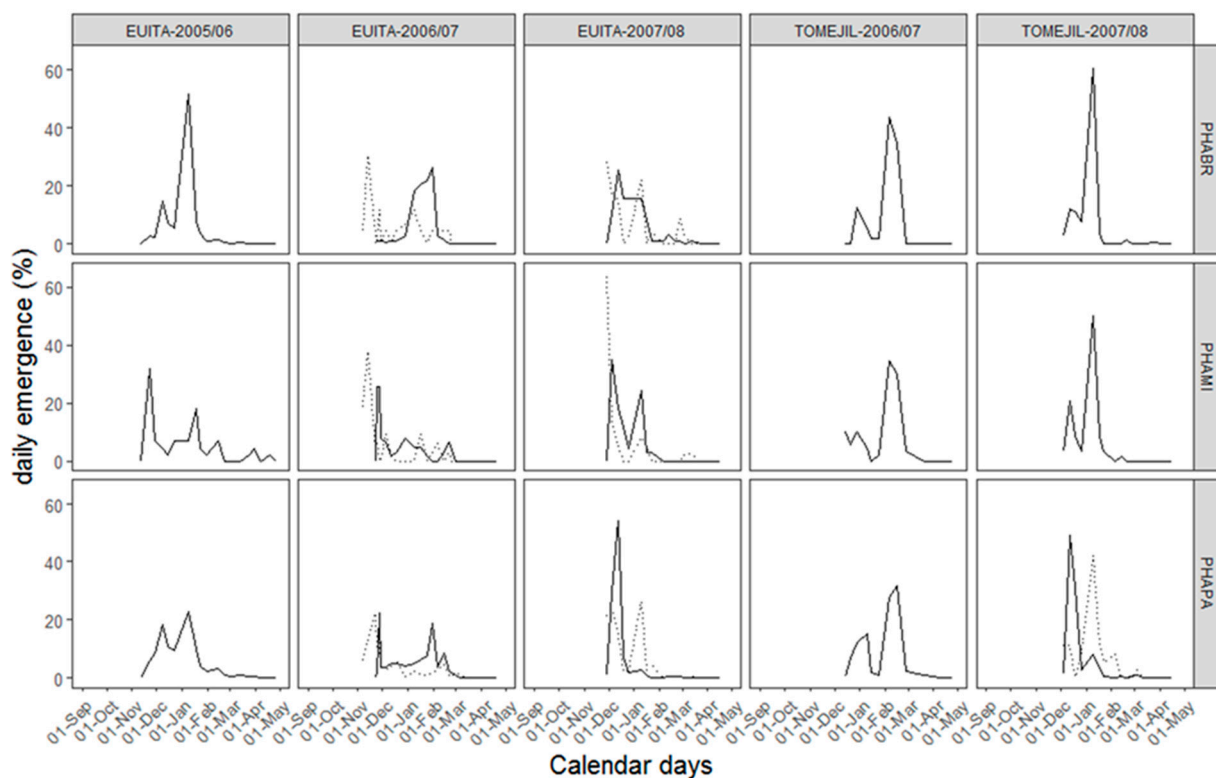

Figure 2. Daily emergence of the three *Phalaris* species at the two experimental locations. Black lines—first season emergence (sowing season); dotted lines—second season emergence (from the remaining seed bank). PHABR: *Phalaris brachystachys*; PAHMI: *P. minor*; PHAMPA: *P. paradoxa*.

3.3. Accuracy of the Parametric Model

The biological parameters established for *Phalaris* species were very similar, setting 1 °C as T_b for the three of them. Additionally, T_o and T_c were established at 9.9 °C and 22.4 °C, 10.0 °C and 21.2 °C and 11.8 °C and 22.8 °C for *P. brachystachys*, *P. paradoxa* and *P. minor*, respectively. On the other hand, the Ψ_b was established at −1.0 MPa for *P. paradoxa* and *P. minor*, whereas it was established at −1.1 MPa for *P. brachystachys*.

The parameters of the Weibull equation are defined in Table 6. Regarding these equations, *Phalaris* species achieved 50% emergence between 24 and 30 cumulated daily thermal degrees (DTD) for TT and between 22 and 39 cumulated daily hydrothermal degrees (DTD) for HTT.

Table 6. Parameters of Weibull Equation (1) for the thermal and hydrothermal time-based models of the three *Phalaris* species.

Model	*P. brachystachys*		*P. paradoxa*		*P. minor*	
	K	**b**	**k**	**b**	**k**	**b**
TT	8.264187	2.134985	5.161581	1.401254	4.589567	1.3303
HTT	9.231423	2.410334	6.093273	1.747469	4.711248	1.402724

According to the accuracy of the parametric models, TT models for each species presented average RMSE values between 10.9 and 14.5. The most accurate model was for *P. minor*, in which an excellent accuracy (RMSE ≤ 5) was achieved in one situation, good accuracy (5 < RMSE ≤ 10) in four more situations and sufficient accuracy (10 < RMSE ≤ 15) and unsuccessful accuracy (RMSE > 15) in one situation each (Table 7). On the other hand, *P. paradoxa* and *P. brachystachys* presented a good fit in two and three situations, sufficient in one and four situations and unsuccessful in four and one more situation, respectively (Table 7, Figure 3).

Table 7. Root mean square error (RMSE) values obtained from thermal (TT) and hydrothermal (HTT) time-based Weibull models for each *Phalaris* species.

Location	Sowing	*P. brachystachys*		*P. paradoxa*		*P. minor*	
		TT	**HTT**	**TT**	**HTT**	**TT**	**HTT**
ETSIA	S06YR06	10.2	8.2	5.6	5.3	7.3	9.5
ETSIA	S06YR07	10.0	11.1	10.7	8.8	5.4	6.4
ETSIA	S07YR07	13.0	13.5	8.2	12.8	9.5	8.5
ETSIA	S07YR08	5.5	7.0	7.5	12.3	3.4	5.3
ETSIA	S08YR08	11.1	10.0	19.9	14.7	8.5	7.6
Tomejil	S07YR07	24.7	15.9	24.4	22.2	30.4	26.4
Tomejil	S07YR08	-	-	22.2	13.0	-	-
Tomejil	S08YR08	13.7	34.8	17.3	24.5	11.9	16.5
Average		12.6	14.4	14.5	14.2	10.9	11.5

Scarce seedling emergence did not allow fitting the models to the data from *P. brachystachys* and *P. minor* at Tomejil-S07YR08.

Regarding the HTT model, soil moisture did not improve the model accuracy for *P. minor* and *P. brachystachys*; however, it slightly increased the precision for *P. paradoxa*, reducing the RMSE value from 14.5 to 14.2 (Table 7, Figure 3).
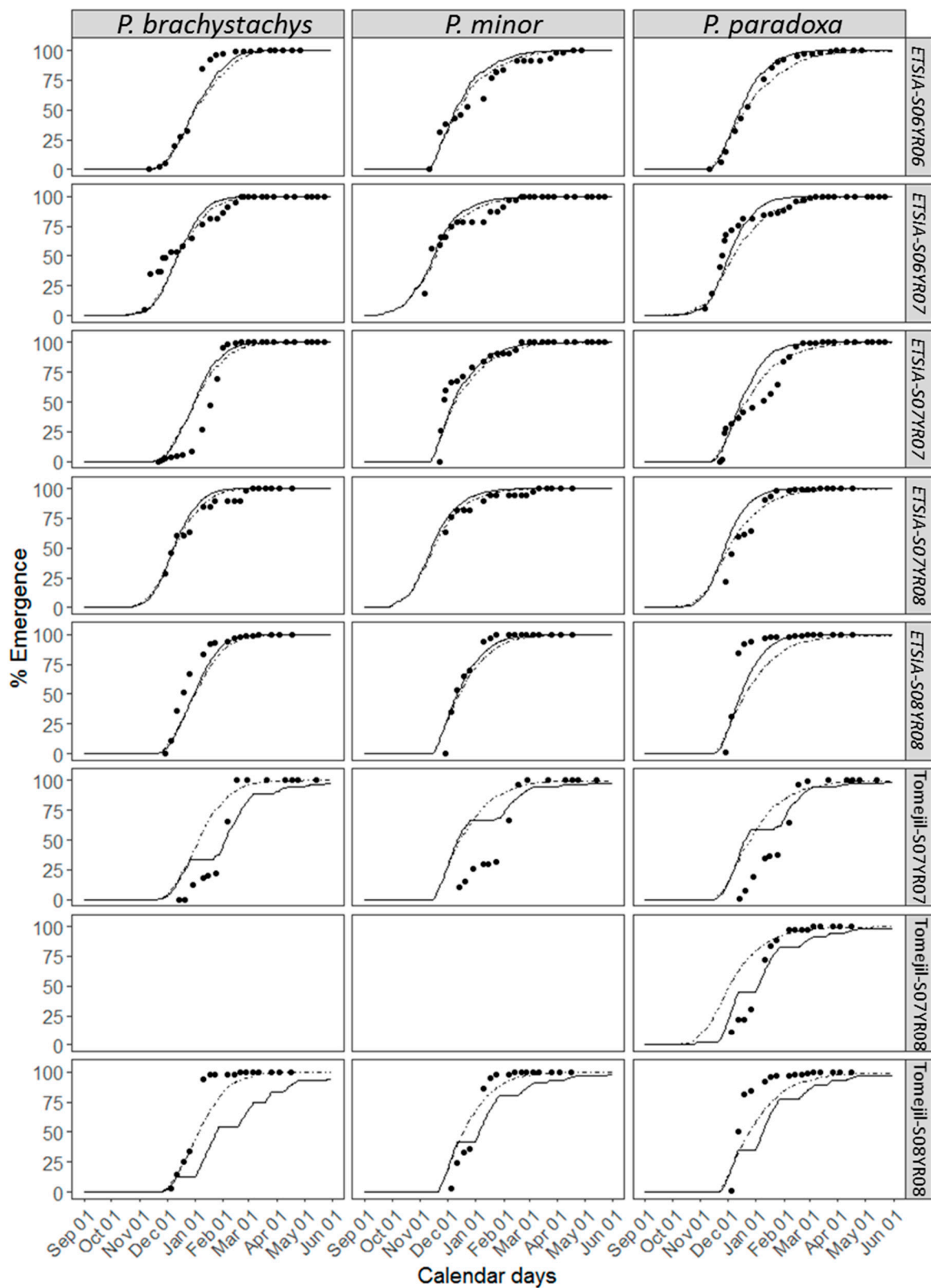
Figure 3. Predicted emergence for the three *Phalaris* species, using thermal (dotted line) and hydrothermal (black line) time-based Weibull models at each location and for the first and second seasons in each plot. Black dots—observed (mean) seedling emergence. Scarce seedling emergence did not allow fitting the models to the data in *P. brachystachys* and *P. minor* at Tomejil-S07YR08.

3.4. Accuracy of the Non-Parametric Model

The best combinations of the three cardinal temperatures for the non-parametric models were different from those established with the parametric model. T_b, T_o and T_c were established at 0 °C, 9.8 °C and 23.4 °C for *P. brachystachys*, at −1 °C, 9.8 °C and 22.5 °C for *P. paradoxa* and at 1 °C, 12.3 °C and 22.7 °C for *P. minor*. However, the Ψ_b value for the non-parametric model was the same as for the parametric models.

With the non-parametric TT model, 50% emergence for *P. paradoxa* was reached at 42 cumulated DTD and 90% emergence at 75; whereas 30 and 62 total accumulated DHD were needed for HTT to reach 50% and 90% emergence, respectively. For *P. minor*, TT and HTT models required 32 and 23 accumulated DTD/DHD, respectively, to achieve 50% emergence and 61 accumulated DTD/DHD was required to reach 90% emergence. Finally, the non-parametric models for *P. brachystachys*, required 40 and 67 accumulated DTD/DHD to reach 50% and 90% emergence (Figure 4).
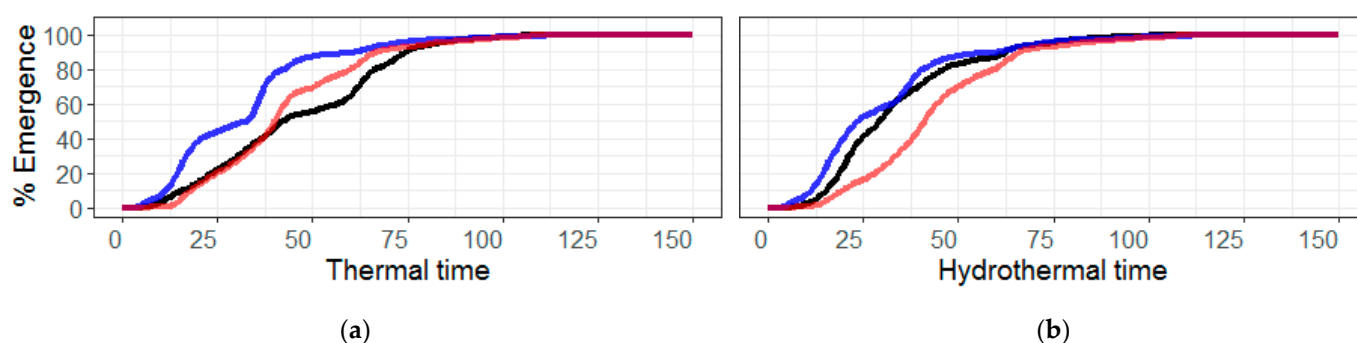

(**a**)　　　　　　　　　　　　　　　　　　　　　　　　　　　　　　　(**b**)

Figure 4. Representation of non-parametric thermal (**a**) and hydrothermal (**b**) time models for *Phalaris brachystachys* (red), *Phalaris minor* (blue) and *Phalaris paradoxa* (black).

The RMSE values for the TT-based models of the three *Phalaris* species were between 10.9 and 15.8. The most accurate model was obtained for *P. minor*, which was excellent for one situation, good for four more situations and sufficient and unsuccessful in one situation each. The accuracy of the *P. brachystachys* model was good in three situations, sufficient in another three and insufficient in one situation; however, the models for *P. paradoxa* only obtained excellent accuracy in one situation, good in another, sufficient in two more and unsuccessful in four situations (Table 8, Figure 5).

Table 8. Root mean square error (RMSE) values obtained from thermal (TT) and hydrothermal (HTT) time non-parametric models for each *Phalaris* species.

Location	Sowing	P. brachystachys		P. paradoxa		P. minor	
		TT	HTT	TT	HTT	TT	HTT
ETSIA	S06YR06	7.9	8.0	12.3	3.6	7.3	9.7
ETSIA	S06YR07	9.9	11.1	16.6	7.1	5.4	5.5
ETSIA	S07YR07	13.4	12.7	7.5	12.2	9.5	11.3
ETSIA	S07YR08	6.5	6.5	4.3	12.4	3.4	3.6
ETSIA	S08YR08	11.1	12.1	29.8	16.5	8.5	6.6
Tomejil	S07YR07	26.4	13.9	13.7	21.0	30.4	22.3
Tomejil	S07YR08	-	-	15.2	13.6	-	-
Tomejil	S08YR08	11.4	36.5	27.1	28.3	11.9	17.8
Average		12.4	14.4	15.8	14.4	10.9	11.0

The missing values of *P. brachystachys* and *P. minor* at Tomejil-S07YR08 are due to the lack of enough seedling emergence to apply the models.
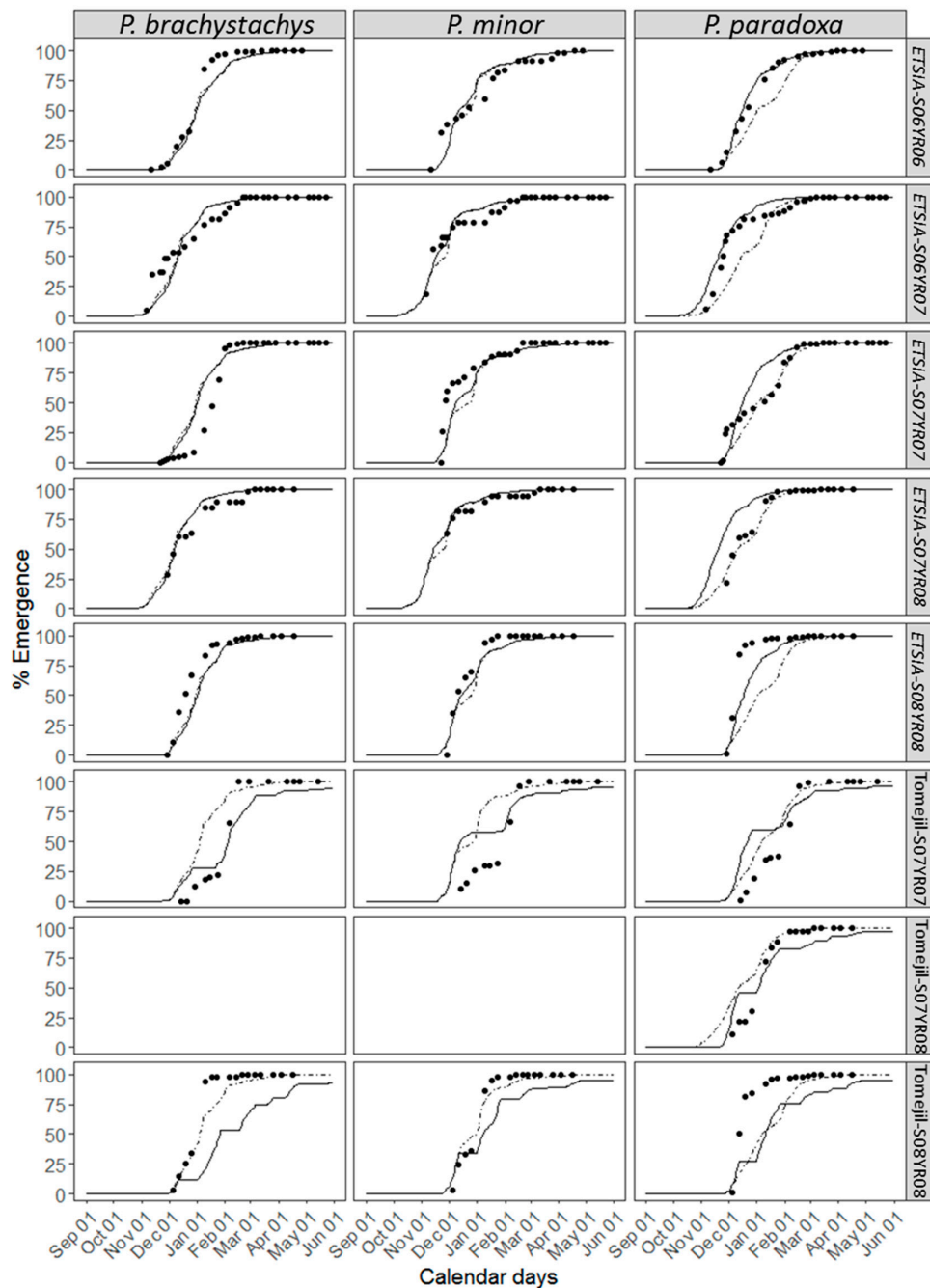
Figure 5. Predicted emergence of the three *Phalaris* species using thermal (dotted line) and hydrothermal (black line) non-parametric model at each location and for the first and second seasons in each plot. The black dots show observed seedling emergence. The missing values of *P. brachystachys* and *P. minor* at Tomejil-S07YR08 are due to the lack of enough seedling emergence to apply the models.

Concerning the HTT models, the soil moisture had only slightly improved the precision for the *P. paradoxa* model, reducing the RMSE value from 15.8 to 14.4 (Table 8, Figure 5).

3.5. Validation of the Models with Independent Data Sets

Although the validation of the parametric and non-parametric models with the independent data was similar, the consideration of the soil moisture increased the precision of the parametric and non-parametric HTT-based models for *P. minor* and *P. paradoxa* with

respect to the TT-based ones; however, this did not happen for *P. brachystachys* (Table 9, Figure 6).

Table 9. Root mean square error (RMSE) values obtained from thermal (TT) and hydrothermal (HTT) times of parametric and non-parametric models at each validation location. Numbers in bold show the lowest RMSE value in each location and season.

| Weed	Experiment	Parametric Model		Non-Parametric Model	
		TT	HTT	TT	HTT
P. brachystachys	ETSIA-2018/19	15.3	16.3	15.7	17.1
	Sevilla Garden-2016/17	28.7	28.5	27.7	29.5
	Sevilla Garden-2018/19	12.5	12.2	11.3	12.2
	Average	18.9	19.0	18.2	19.6
P. minor	ETSIA-2018/19	9.2	8.8	9.6	7.6
	Sevilla Garden-2016/17	31.9	30.5	32.7	31.0
	Sevilla Garden-2017/18	12.7	11.2	14.3	12.3
	Sevilla Garden-2018/19	7.5	5.8	7.6	5.9
	Average	15.4	14.1	16.1	14.2
P. paradoxa	Burgos-2019/20	10.6	6.8	16.9	4.2
	ETSIA-2018/19	12.3	11.6	19.7	11.2
	ETSIA-2019/20	9.9	12.4	8.5	12.1
	Guadalcazar-2019/20	14.8	17.7	11.7	15.8
	Huesca-2019/20	11.1	9.3	17.0	8.5
	Sevilla Garden-2017/18	18.0	12.9	25.7	13.6
	Tomejil-2019/20	16.4	9.5	9.2	12.9
	Valladolid-2019/20	14.6	8.6	20.2	6.3
	Average	13.5	11.1	16.1	10.6
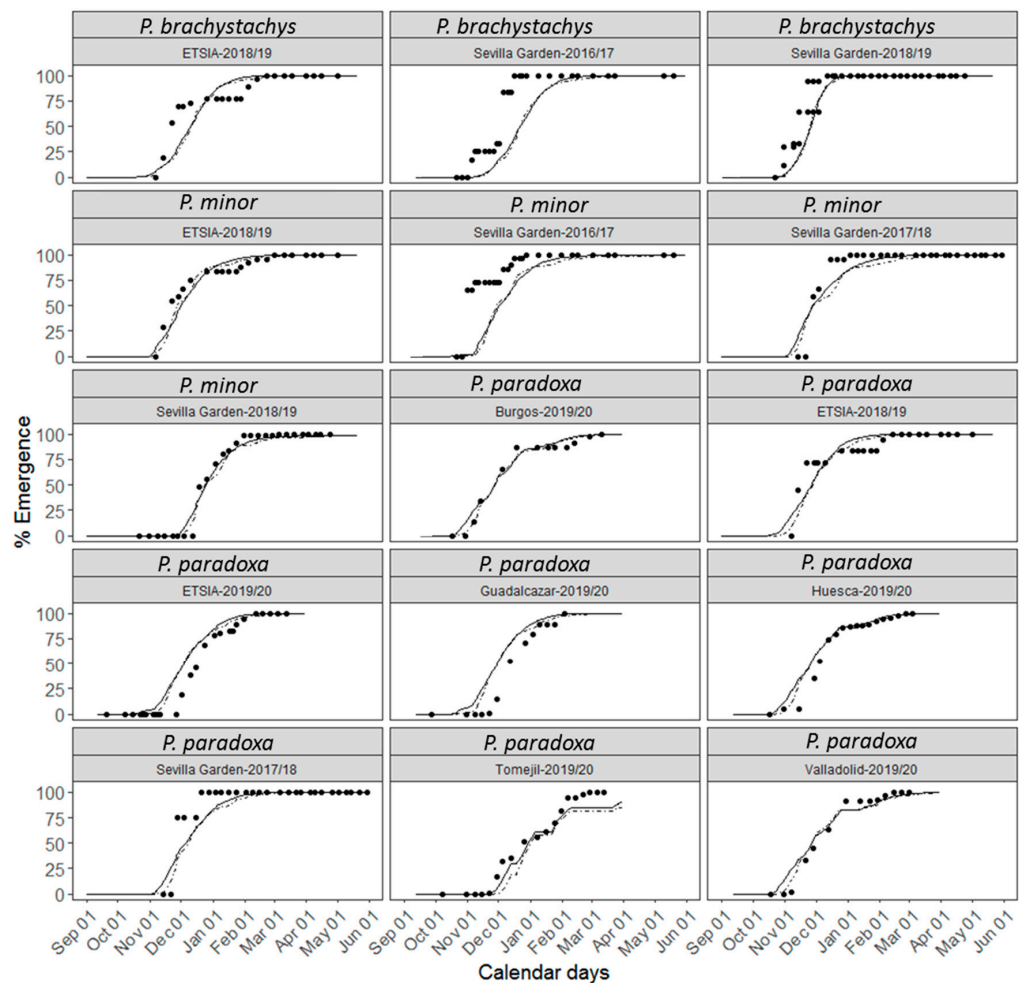
Figure 6. Predicted emergence of the three Phalaris species using parametric (black line) and non-parametric (dotted line) hydrothermal model at each validation location. The black dots show observed seedling emergence.

The models for *P. brachystachys* showed lower accuracy than the models of the other two *Phalaris* species for the description of the independent data. In this case, the *P. brachystachys* model only achieved sufficient accuracy at one location out of three and was best with the non-parametric TT model. On the contrary, *P. minor* and *P. paradoxa* models were successfully validated with the independent data. In the case of *P. minor*, the RMSE values were successful at three of the four studied locations (Table 9, Figure 6), with the parametric HTT model obtaining the highest accuracy. Further, HTT reduced the RMSE values for parametric and non-parametric models at all validation locations. Concerning *P. paradoxa*, the models were successfully validated at the eight locations, where the non-parametric HTT model was the most accurate; in this case, the soil moisture reduced the RMSE values at five out of eight locations.

4. Discussion

4.1. Emergence Pattern

Similar to the observations of Jiménez-Hidalgo [11] and Taylor et al. [30], the emergence patterns of the three *Phalaris* species were similar, with the first seedlings observed in November and the last ones in March or even April, depending on the season, but in all cases with two flushes during the emergence season, the first one in December and the second in February. Both flushes occurred when the mean air temperature was close to the optimum temperature, between 9 °C and 13 °C, and was separated by a period when the mean air temperature dropped below 9 °C.

When we compared the emergence of the *Phalaris* species to that of other problematic winter weeds in the south of Spain, we found that they were similar to that of winter wild oat (*Avena sterilis* subsp. *ludoviciana* (Durieu) Gillet and Magne), of which the emergence period also lasts from November to March [31]. On the contrary, *Phalaris* showed more staggered emergence periods than north African knapweed (*Centaurea diluta* Aiton), which emerges between late October and early January [25], or ryegrass (*Lolium rigidum* Gaudin), which emerges from November to February [24]. The wide emergence period of the *Phalaris* species could also contribute to their presence as problematic weeds in summer crops.

4.2. Threshold Parameters (T_b, T_o, T_c and Ψ_b)

The three cardinal temperatures (T_b, T_o and T_c) were similar between models and species. The T_b ranged from −1 °C to 1 °C, which is a similar to that used by González-Andújar et al. [20] for *P. paradoxa*, who established this parameter at 0.8 °C; lower than that established by Mesgaran et al. [32] and Derakhshan et al. [22] for *P. minor* (3.5 °C and 4.7 °C, respectively), but the latter were estimated for germination under controlled conditions in germination chambers and might vary from required field conditions for emergence.

The established T_o, between 9.9 °C and 12.3 °C, was also lower than that set under controlled conditions by Derakhshan et al. [22], who established them between 22.6 and 29.6 °C. The differences between the results observed in the present manuscript and those from Derakhshan et al. [22] might be explained because the authors established a T_o for germination, and because seeds belong to a population growing at a completely different climate (north of Iran) and temperature requirements could easily be different. However, the T_o estimated in the present work is in agreement with values estimated in field conditions by Jiménez-Hidaldo [11] and Taylor et al. [30], who describe an optimum range between 10–15 °C and 10–17 °C, respectively. Similar to T_b and T_o, T_c was also lower than that established under controlled conditions [22,33], but this parameter has not been previously estimated in field conditions for *Phalaris* species in any other work, and thus, no comparison is possible.

Concerning Ψ_b, no significant differences were found between the three *Phalaris* species: it was set to −1.1 MPa for *P. brachystachys* and −1 MPa for the other two species. Despite this, *P. brachystachys* was shown to be a little more tolerant to drought conditions for the emergence; this is in agreement with observations from Alcantara et al. [34], who described a higher drought tolerance by *P. brachystachys* than *P. minor* during growth stages.

Apart from soil temperature and moisture, other factors are known to affect the start of the emergence process, considering this process from dormancy release to the emergence of cotyledons on the soil surface. Light is known to promote the release of dormant seeds of *Phalaris* species, such as *P. paradoxa* [35] and *P. minor* [36]; however, in the present study, light could only have been a relevant variable at the sowing date, as no further soil disturbance was performed. An interesting future experiment could be established to study the effect of tillage at different dates on the emergence of these *Phalaris* species and the suitability of the models developed in the present manuscript to those emergence patterns.

4.3. Parametric vs. Non-Parametric Models

Although the non-parametric model could have slightly improved the accuracy of the parametric TT-based model for *P. brachystachys* and the HTT-based model for *P. minor*, in practice, both parametric and non-parametric models showed very similar accuracy (Tables 3 and 7, Figures 3 and 5), as is shown by the validation results, which show similar precision to those of the parametric model, with improved accuracy at 9 of 15 experimental locations (Table 8). These results show that non-parametric models have the same capacity to describe and predict weed emergence as classical parametric models, which is somehow in disagreement with the observations from Gonzalez-Andújar et al. [20], who concluded that non-parametric models were only useful for describing and not for predicting weed emergence. These differences could be explained by the fact that Gonzalez-Andújar et al. [20] developed a model for *P. paradoxa* using only data from a single location and year to predict its emergence at the same locations during the next two years. The present work used data from two locations and three seasons; thus, its conclusions are more reliable than those obtained from a single season.

4.4. Applicability of the Models

In this work, emergence models were successfully developed to describe the emergence of three *Phalaris* species, with both parametric and non-parametric statistical tools. Emergence models frequently present limited application due to within-species variation. Very often, models developed in one location cannot be applied to other locations with different agroclimatic conditions because models tend to fail when environmental conditions vary from where they were developed [37]. Moreover, the mother plant effect promotes differences in the dormancy and germination characteristics of the offspring, even in the same population [38]. This has been the case of *L. rigidum*, whose emergence model could successfully be applied in central and north-east Spain, but not in the south [24]. However, in the present work, the three models could be validated with independent data from the same (Guadalcázar, Seville, Tomejil) and from different agroclimatic locations (Burgos, Huesca, and Valladolid) within Spain. This result suggests that the applicability of these models is wider than for other weed species, and that they could be applied with fair accuracy, at least in the whole Iberian Peninsula with a Mediterranean climate. Despite this promising result, the applicability of these models for the emergence of *Phalaris* species in other Mediterranean climatic zones should be checked and be calibrated if necessary.

Ideally, these models should be implemented in software tools together with other already developed models. There already are several models for the emergence of winter weeds in Spain, such as those for *Papaver rhoeas* [37], *L. rigidum* [24], *A. sterilis* [31] or *Bromus diandrus* [39], among others, and an effort should be made to integrate them into a DSS tool, such as AlertInf [40,41], which is being applied in the Venetto region (Italy) with considerable success.

5. Conclusions

The parametric and non-parametric models successfully described the emergence of *P. brachystachys*, *P. minor* and *P. paradoxa*. In addition, both models presented similar results at independent validation data, obtaining good accuracy at one of three, three of

four and eight of eight experimental locations for *P. brachystachys*, *P. minor* and *P. paradoxa*, respectively. Our findings demonstrate that parametric and non-parametric statistical tools can predict the emergence of seedlings under different agroclimatic conditions. These models, especially the non-parametric HTT models, are potentially applicable to actual field situations by providing guidance for DSS to implement weed management tactics.

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