


Modeling emergence of sterile oat (*Avena sterilis* ssp. *ludoviciana*) under semiarid conditions

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Research Article

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Abstract

Winter wild oat [*Avena sterilis* ssp. *ludoviciana* (Durieu) Gillet & Magne; referred to as *A. sterilis* here] is one of the major weed species of the *Avena* genus, given its high competitive ability to infest cereal crops worldwide, with special concern in Spain. A nine-location field experiment was established across Spain where a total of 400 *A. sterilis* seeds per location were sowed in four replicates in autumn 2016 to monitor the emergence during two growing seasons in dryland conditions. The data were used to test the prediction ability of previously published thermal (TT) and hydrothermal time (HTT) models and to develop new models, if required. Overall, the average percentage of emergence was 30% during the first season and 21% during the second season. In both seasons, the main emergence flush occurred between November and February. According to the phenological stage, *A. sterilis* achieved the tillering earlier in southern sites, between November 25 and the end of December, compared with northern sites, where this stage was reached at the end of January. The newly developed model described the emergence with precision, using three cardinal temperatures to estimate the TT. The three cardinal points were established at -1.0 , 5.8 , and 18.0 C for base (T_b), optimum (T_o), and ceiling temperature (T_c), while the base water potential (Ψ_b) was established at -0.2 MPa for the HTT estimation. This study contributes to improving prediction of the emergence of *A. sterilis* and provides knowledge for decision support systems (DSS) for the control of this weed.

Introduction

Wild oats (*Avena* spp.) are among the most widespread and concerning weeds in agriculture (Holm et al. 1977). In Spain, *Avena* sp. are represented mainly by two species, spring or common wild oat (*Avena fatua* L.) and sterile or winter wild oat (*Avena sterilis* L.), the last with an accepted subspecies, *Avena sterilis* ssp. *ludoviciana* (Durieu) Gillet & Magne, referred to hereafter as *A. sterilis*. The most abundant taxon is *A. sterilis*, which is distributed in north and central Spain. *Avena fatua* infests wheat (*Triticum aestivum* L.) crops in the mountainous areas of northern Spain where winters are cold, while *A. sterilis* is more abundant in the warm central and southern regions of the Iberian Peninsula (Fernández-Quintanilla et al. 1997; García Baudín 1982). These tall grasses are considered especially worrisome due to their strong competitive ability, reducing cereal crop yields between 10% and 60% (Bajwa et al. 2017; Fernández-Quintanilla et al. 1997). This success of *A. sterilis* as a weedy species is explained, in part, by its high seed production, earlier shedding of seeds (Barroso et al. 2006), and the capacity of its seeds to remain dormant in the seedbank for several years (Bajwa et al. 2017). Its fecundity can increase the soil seedbank from 100 seeds m^{-2} to more than 1,000 seeds m^{-2} in 2 yr in the absence of control methods (Gonzalez-Andujar and Bastida 2018).

Avena sterilis management has become difficult in recent years with the development of biotypes that are resistant to a large number of herbicides (Heap 2020; Owen and Powles 2009) and with the increase of no-tillage systems, as *A. sterilis* is adapted to different soil tillage systems (Alarcón et al. 2018). For this reason, some studies have been carried out to increase knowledge of this weed's biology and thus improve integrated weed management (IWM) for its control. In

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this sense, phenological stages of this weed are relevant, as they determine its competitive periods (Knezevic and Datta 2015) and the optimal moments for applying a certain control method (Royo-Esnal et al. 2012). For example, according to Owen and Powles (2009), to achieve effective control of *Avena* spp., and in this case for *A. sterilis*, chemical control must be applied in early growth stages.

Seedling emergence is part of the phenological growth process that happens in the early stages of the weeds life cycle, so biological knowledge of this event becomes essential for understanding a species' behavior. This information is even more relevant for annual weeds and can contribute to improved IWM. The principal factors affecting seed germination and seedling emergence are temperature, water potential, air quality, and light (Forcella et al. 2000). Soil temperature can be used by itself to develop thermal time (TT) models, as the accumulation of daily thermal degrees (DTD) can be used to predict weed emergence. According to Bradford (2002), TT is defined by three cardinal points that are different for each species. The first is the base temperature (T_b), which is the temperature when the accumulation of DTD starts and below which no accumulation on DTD happens. Above T_b , an increase in temperature produces more DTD accumulation until the optimal temperature (T_o) is reached, which is the temperature when maximum DTD accumulation is produced. At temperatures greater than the T_o , DTD accumulation decreases until reaching the ceiling temperature (T_c), after which there is no DTD accumulation. TT models can be corrected to accumulate DTD only when there is enough soil moisture; such models are called hydrothermal time (HTT) models (Grundy 2003). The accumulation of daily hydrothermal degrees (DHD) for emergence models is considered to occur when the water potential (Ψ) is above a base water potential (Ψ_b) that varies with species and depends on their tolerance of soil aridity.

The first approach to modeling *A. sterilis* emergence was performed by Fernández-Quitanilla et al. (1986), who related the emergence of this weed with the cumulative rainfall. Then, an HTT model was developed by Leguizamón et al. (2005), using T_b and Ψ_b as the only base parameters previously obtained from a growth chamber experiment (Fernández-Quintanilla et al. 1990), which were established at -0.8 C and at -1.2 MPa, respectively. Thus, the aim of this study is to check the precision of the developed model across 24 situations. Moreover, the development of a new model using the three cardinal thermal points is proposed as a second objective, in order to compare it with the previous model from Leguizamón et al. (2005) and to consider whether the accuracy will be enhanced.

Material and Methods

Plant Material

Seeds of *A. sterilis* were collected from approximately 20 plants in July 2016 from a barley (*Hordeum vulgare* L.) field margin in Cubells, in the province of Lleida, Spain (41.85°N , 0.95°E). Seeds were cleaned and dry-stored in a refrigerator at 4 C until their distribution to the different participants of the experiment in September 2016. Once received, they were sown in the field during October 2016.

Experimental Design

The experiment was established in October 2016 at nine sites across Spain (Figure 1). At seven sites, the experiment was carried out during

two growing seasons; while at the two remaining sites, the experiment was only conducted during the first year (Table 1). The emergence of *A. sterilis* was monitored under rainfed conditions in an attempt to simulate the cereal field conditions where this weed is a concern for farmers. The experiment followed a randomized block design where each location had four replications, which consisted of 0.25 m by 0.25 m quadrats. For each replicate, 6.25 L of soil was extracted, mixed with the 100 seeds, and then returned to the ground so that the seeds were evenly distributed in the upper 10 cm of the soil. An unseeded quadrat was established in each replication to check whether the natural *A. sterilis* populations would interfere with the results. Seedling emergence was recorded weekly with destructive counts from October until May, except during emergence flushes, when data were collected every 2 to 3 d. To observe the early growth under different environments, the first two emerged seedlings from each replicate were maintained in five northern and four southern sites and were allowed to grow until the end of December. Phenological stages of these seedlings were recorded based on the Biologische Bundesanstalt, Bundessortenamt and Chemical (BBCH) industry scale (Meier 2001). Soil temperature at 2-cm depth and rainfall were recorded at each location using a digital thermometer DS18B20 (Maxim, San José, California, USA) and a pluviometer D2145 (Darrea, Llobregat, Spain) within the experimental area. The experimental design is accurately described in Sousa-Ortega et al. (2020a).

In this paper, we define the cumulative emergence as the percentage of emerged seedlings from the total emerged seedlings by experimental location and year. Seedbank emergence is the percentage of emerged seedlings from the total seeds sown.

Evaluation of the Previously Published Model

The observed emergence was subjected to the model developed by Leguizamón et al. (2005) for the emergence of *A. sterilis*. The TT [Equation 1] and HTT [Equation 2] models used are:

$$\text{TT model : } Y = 1 - e^{[-\log 2 * (\frac{TT}{344.3})^{2.09}]} \quad [1]$$

$$\text{HTT model : } Y = 1 - e^{[-\log 2 * (\frac{HTT}{207.7})^{1.53}]} \quad [2]$$

where Y is the cumulative emergence, TT is the thermal time, and HTT is the hydrothermal time. TT and HTT were calculated with the sum of DTD and DHD, respectively, following the equations:

$$\text{If } T > -0.8\text{C : } \text{DTD} = T - 0.8\text{C}$$

$$\text{If } T < -0.8\text{C : } \text{DTD} = 0$$

$$\text{If } \psi > -1.2\text{MPa : } \text{DHD} = \text{DTD}$$

$$\text{If } \psi < -1.2\text{MPa : } \text{DHD} = 0$$

where T is the soil temperature in degrees Celsius and Ψ is the soil water potential in megapascals (MPa).

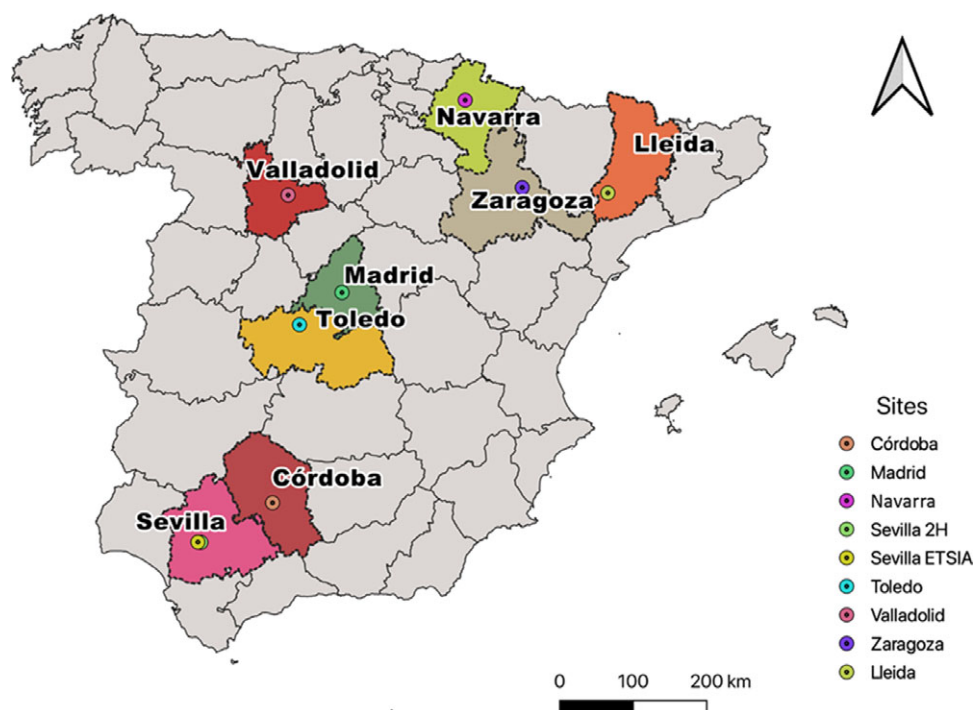
Development of the New Emergence Model

The three cardinal temperatures for TT, T_b , T_o , and T_c , were estimated in a first step. These values were obtained through an iterative process, wherein different combinations of these cardinal temperatures were used to calculate the TT; then a nonlinear regression between TT and observed emergence was tested using three biological equations (Equations 3–5), and the cardinal temperatures combination with lower errors (root mean-square error

Table 1. Location, sowing date, and soil texture for the nine experimental field sites established in Spain in 2016 to study *Avena sterilis* emergence.

	Location	Latitude	Longitude	Sowing dates	Soil texture		
					Sand	Silt	Clay
				October	%		
1	Córdoba	37.8589°N	4.8008°W	17	35	35	30
2	Lleida	41.6281°N	0.5922°E	11	31	38	31
3	Madrid	40.4581°N	3.7503°W	10	75	7	18
4	Pamplona	42.8178°N	1.7217°W	11	34	39	27
5	Sevilla 2H	37.3503°N	5.8931°W	11	36	31	33
6	Sevilla ETSIA	37.3519°N	5.9389°W	11	39	29	32
7	Toledo ^a	40.0550°N	4.4258°W	11	50	21	29
8	Valladolid ^a	41.6469°N	4.6469°W	18	27	32	41
9	Zaragoza	41.7294°N	0.8078°W	7	28	41	31

^aLocation where the experiment was conducted only during 2016–2017 season.

**Figure 1.** Locations within Spain where the experiments of *Avena sterilis* ssp. *ludoviciana* emergence were conducted during the 2016–2017 and 2017–2018 seasons.

[RMSE]; Equation 6) was selected. The second step was to estimate Ψ following a similar process that was carried out for estimating TT; in this case, different base water potentials (Ψ_b) were used with the combination of the best three cardinal temperatures previously selected to estimate the HTT.

TT and HTT were calculated by summing the DTD and DHD. In this work, the DTD and DHD were obtained following Bradford (2002):

If the soil temperature was between T_b and T_o : $DTD = T - T_b$

If the soil temperature was between T_o and T_c : $DTD = (T - T_b) * [1 - (T - T_b)/(T_c - T_b)]$ and if $T < T_b$ or $T > T_c$, then $TT = 0$

where T is the mean daily temperature.

DHD time was estimated by including soil moisture in the DTD calculations.

$$DHD = DTD * (\Psi - \Psi_b)$$

where if $\Psi < \Psi_b$, then $(\Psi - \Psi_b) = 0$; if $\Psi > \Psi_b$, then $(\Psi - \Psi_b) = 1$.

As a first step to obtain Ψ , which was used in these equations, a water balance was performed, using the procedure defined in Fuentes-Yagüe and García-Legaspi (1999) to get the water content. Soil texture and organic matter content were used to estimate the water-holding capacity of the soil; then the water balance was calculated by summing the rainfall and estimating the evapotranspiration (obtained from the closest meteorological station). Once the water content was calculated, the water potential was estimated following the equations described in Saxton and Rawls (2006).

Thus, a reduction in DTD was established when the temperature was above T_o , because a slight reduction between T_o and T_c better explains the biological consequences than a drastic reduction when the temperature is above T_c . Moreover, as the three cardinal points were established by an iterative process using numerous combinations, an eventual result with similar values of T_o and T_c would suggest that this slight reduction in TT is not necessary.

The biological growth models tested in the nonlinear regression were: Gompertz [Equation 3], log-logistic [Equation 4], and Weibull [Equation 5] equations:

Table 2. Location, sowing code, sowing date, date of the first relevant rainfall, and total number of *Avena sterilis* seedlings counted for each validation series.

Location	Code ^a	Sowing date	First relevant rainfall ^b	No. of seedlings ^c
Sevilla ETSIA	S06YR06	November 11, 2005	November 14, 2005	73
Sevilla ETSIA	S06YR07		September 13, 2006	176
Sevilla ETSIA	S07YR07	November 12, 2006	November 16, 2006	368
Sevilla ETSIA	S07YR08		September 21, 2007	29
Sevilla ETSIA	S08YR08	November 15, 2007	November 20, 2007	152
Tomejil	S07YR07	November 15, 2006	November 16, 2006	203
Tomejil	S07YR08		September 21, 2007	65
Tomejil	S08YR08	November 20, 2007	November 22, 2007	237

^aThe code represents the year when sowing was performed and the year when the emergence was counted; i.e., the “S06YR07” code indicates that seeds were sown in 2005–2006 and that emergence was counted during 2006–2007.

^bFirst relevant rainfall is the starting point for the accumulation of thermal and hydrothermal time.

^cSum of total emerged seedlings from four replications with 200 seeds planted in each replication for a total of 800 seeds planted at each location.

$$Y = 100 * e^{[-e^{(-k*TT+b)}]} \quad [3]$$

$$Y = 100/[1 + e^{(-k*TT+b)}] \quad [4]$$

$$Y = 100 * \{1 - e^{[-e^{(-k)*TT^b}]}\} \quad [5]$$

where Y is the cumulative emergence, TT is the thermal time (HTT if this scale is used), and k and b are parameters obtained from the nonlinear regression. In the Gompertz and log-logistic equations, an increase in b represents a delay of the inflection point that represents 36% and 50% of weed emergence, respectively. An increase of the k parameter produces an increase in slope at the inflection point. On the other hand, in the Weibull equation, both parameters do not have biological meaning; they are simply shaping the emergence curve.

The accuracy of these models was tested with the RMSE [Equation 6], where greater model accuracy is indicated by lower RMSE values. Model accuracy was assessed using RMSE with the scale developed in Royo-Esnal et al. (2010) to evaluate their artificial seedbank experiment. A model with an RMSE <5 has excellent accuracy, between 5 and 10 it has very good accuracy, between 10 and 15 it has good accuracy, and it is inaccurate for values >15.

$$RMSE = \sqrt{1/n \sum_{i=0}^n (x_i - y_i)^2} \quad [6]$$

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.

Model Validation

The selected model was applied to a seedling emergence data of an *A. sterilis* population collected from a wheat farm in Jerez (southern Spain) to evaluate its predictive ability. The independent data were obtained from a previous experiment that was carried out in two different sites, Tomejil (37.4023°N, 5.5893°W) and Sevilla ETSIA (same site described in Table 1), during two (2006 to 2007 and 2007 to 2008) and three (2005 to 2006, 2006 to 2007, and 2007 to 2008) growing seasons, respectively. The soil structure at Tomejil was 6% sand, 34% silt, and 60% clay.

At both locations, four replications of 200 seeds of *A. sterilis* were sown each growing season, following the same procedure described earlier. Each year, newly sown plots were placed next to those of the previous season, without disturbing the soil of the existing plots, and thus allowing recording the emerged

seedlings from each plot during two growing seasons. DTD and DHD accumulation began at the date of the first relevant rainfall, and subsequent emergence data were then combined to produce eight different situations in which the model could be tested (Table 2). Climatic data for both sites were collected from the nearest weather station, and water potential was estimated using the same procedure described earlier.

Seedbank Emergence

Differences in total seedling emergence among locations were analyzed with one-way ANOVA for each season. Differences among means were determined using Tukey's test at $P < 0.05$. As was mentioned before, the seedbank emergence is referred to the percentage of total emerged seedlings from the total seeds sown, independent of seed viability. This is possible because, as only one population was used, the proportion of nonviable seeds is supposed to be the same among locations, and the observed differences could be explained by the different environmental conditions at each site. Moreover, no *A. sterilis* was recorded in the controls; therefore, the natural seedbank did not affect to the differences between locations.

Results and Discussion

Weather Conditions

The experimental sites had different weather conditions during both growing seasons (from October to April), providing robustness to the model. The mean temperature during the entire experiment was, as expected, higher in the experiment carried out in Sevilla (17.0 and 15.9 C for 2016 to 2017 and 2017 to 2018, respectively), while the coldest locations were Valladolid, Navarra, and Madrid, with mean monthly temperatures of 10.4, 10.6, and 11.8 C in 2016 to 2017 and 9.6, 9.5, and 10.9 C in 2017 to 2018, respectively (Table 3). With respect to precipitation, the average of total rainfall between October and April was 370.2 ± 40.4 mm in 2016 to 2017 and 386.6 ± 36.7 mm for 2017 to 2018. Although total rainfall was similar (only 16 mm of difference between the two seasons), autumn 2017 to 2018 was drier than in 2016 to 2017, especially at Zaragoza and Lleida, where 29.4 and 19.0 mm, respectively, were recorded from October to December (Table 4).

Emergence Pattern

The average seedbank emergence of *A. sterilis* was 30% in 2016 to 2017 and 21% in 2017 to 2018 (Table 5). *Avena sterilis* seedbank

Table 3. Average monthly temperature for the nine different experimental sites from October to April during seasons 2016–2017 and 2017–2018, with average temperature of the emergence period also provided.

	Córdoba	Lleida	Madrid	Navarra	Sevilla 2H	Sevilla ETSIA	Toledo	Valladolid	Zaragoza
	C								
October 2016	20.4	17	16.4	14.8	23.9	23.9	18	14.7	16.9
November 2016	13.2	9.8	8.9	8.9	15.4	15.4	10.3	7.4	10.4
December 2016	11.4	4.9	7.5	5.6	12.5	12.5	8.6	5.1	6.2
January 2017	8.7	4.4	4.8	4.1	10.2	10.2	6.7	4.1	6.5
February 2017	12.2	9.3	8.5	8.2	13.9	13.9	9.6	8	10.2
March 2017	13.8	12.6	10.9	10.7	17.8	17.8	11.8	10.4	13.7
April 2017	16.8	15.1	14.8	11.8	25	25	16.4	13.5	15.4
Average 2016–2017	13.8	10.4	10.3	9.2	17.0	17.0	11.6	9.0	11.3
October 2017	21.9	17.8	17.6	15.4	26.2	26.2	20.2	16.6	18.6
November 2017	13.4	9	9.4	8.1	15.8	15.8	11.3	7.8	10.5
December 2017	8.8	4	6.1	5.1	10.2	10.2	7.3	4.8	7.2
January 2018	9.1	7.9	6.8	6.1	11.1	11.1	7.5	5.2	8.7
February 2018	9	5.9	5.5	4	13.4	13.4	6.8	4.5	6.8
March 2018	11.9	10.5	8.6	8	15.1	15.1	8.8	7.3	10.9
April 2018	15.7	14.7	12.5	12.5	19.3	19.3	13	11.9	14.8
Average 2017–2018	12.8	10.0	9.5	8.5	15.9	15.9	10.7	8.3	11.1

Table 4. Total monthly precipitation for the nine different experimental sites from October to April during seasons 2016–2017 and 2017–2018, with total precipitation for the emergence period also provided.

	Córdoba	Lleida	Madrid	Navarra	Sevilla 2H	Sevilla ETSIA	Toledo	Valladolid	Zaragoza
	mm								
October 2016	84	44.4	66.7	23.7	117.9	117.9	91.4	49.4	34.6
November 2016	142.2	41	53	115.3	103.3	103.3	157.6	54.2	85
December 2016	45	5.2	35	1.4	62.8	62.8	62.4	13.4	3
January 2017	20	12.4	20.2	109.5	12	12	27	10.2	13.2
February 2017	50.8	13	51	37.9	48.7	48.7	74.4	33.2	25
March 2017	73.6	85.4	16.7	79.6	53	53	24.2	6.4	38
April 2017	67.4	15.2	13.2	24.6	48.5	48.5	20.4	7	5.8
Total 2016–2017	486	227.8	262.4	414.6	458	458	460.8	183.6	207.8
October 2017	0.2	14	0	18.6	0	0	0	0.2	4.2
November 2017	27.4	19.8	28.7	17	12.9	12.9	13.8	4.6	5
December 2017	52.4	2	8.9	59.4	61.8	61.8	28.4	19.2	6.2
January 2018	36	7.6	19.9	113.5	28.1	28.1	104	26.6	7.8
February 2018	68.2	24.6	50	172.8	69.9	69.9	23.2	42.4	51.8
March 2018	27.6	30.2	67.2	73.7	16.3	16.3	90	41.4	28.4
April 2018	262.4	32.4	148.3	79.7	126.8	126.8	250.6	117.6	32.4
Total 2017–2018	536.8	200.4	379.4	697.5	393.5	393.5	617	318.8	250

emergence in the first season was lower than for two other species that are of concern in wheat fields in Spain, rigid ryegrass (*Lolium rigidum* Gaudin; 58%) and North African knapweed (*Centaurea diluta* Aiton; 39%) (Sousa-Ortega et al. 2020a, 2020b). The longer seed dormancy of *A. sterilis*, which can reach up to 5 yr (Bajwa et al. 2017), might explain this result. For this reason, *A. sterilis* seedling emergence was higher during the second season, and thus seed-bank reduction was less than for the other two weeds.

Comparing seedbank emergence between locations, statistical differences were found in the first (P -value < 0.0001) and second seasons (P -value < 0.0001) (Table 5). The highest seedling emergence occurred at Zaragoza (64%), which was statistically similar to emergence at Lleida (45%), which was followed by Valladolid (40%), Madrid (35%), and Navarra (35%). Experimental sites with low seedling emergence were Cordoba (9.5%), Toledo (9.5%), and Sevilla ETSIA (8.5%) (Table 5). These results show a trend of increased *A. sterilis* emergence at cooler locations,

Table 5. Average percentage emergence (\pm SD) of *Avena sterilis* at nine experimental locations in Spain during seasons 2016–2017 and 2017–2018.

Location	Emerged ^a		Nonemerged
	2016–2017	2017–2018	2016–2018
	%		
Córdoba	9.5 (3.32)d	7.3 (3.20)b	83.3 (2.06)
Lleida	45.0 (11.83)ab	22.8 (4.11)b	32.3 (12.50)
Madrid	35.3 (9.03)bc	26.5 (14.53)b	38.3 (8.38)
Pamplona	35.0 (2.58)bc	15.5 (7.55)b	49.5 (10.12)
Sevilla 2H	25.8 (11.03)c	50.0 (12.25)a	24.3 (22.43)
Sevilla ETSIA	8.5 (2.65)d	10.0 (8.45)b	81.5 (10.91)
Toledo	9.5 (3.51)d	—	—
Valladolid	40.0 (5.89)bc	—	—
Zaragoza	64.0 (11.92)a	11.3 (1.50)b	24.7 (13.40)
Average	29.6 (18.50)	20.5 (15.85)	24.8 (17.72)

^aDifferent letters show significant differences according to Tukey's test ($\alpha = 0.05$). Data for 2016–2017 were transformed ($x^{0.5}$) to meet requirements for ANOVA, but nontransformed means are shown.

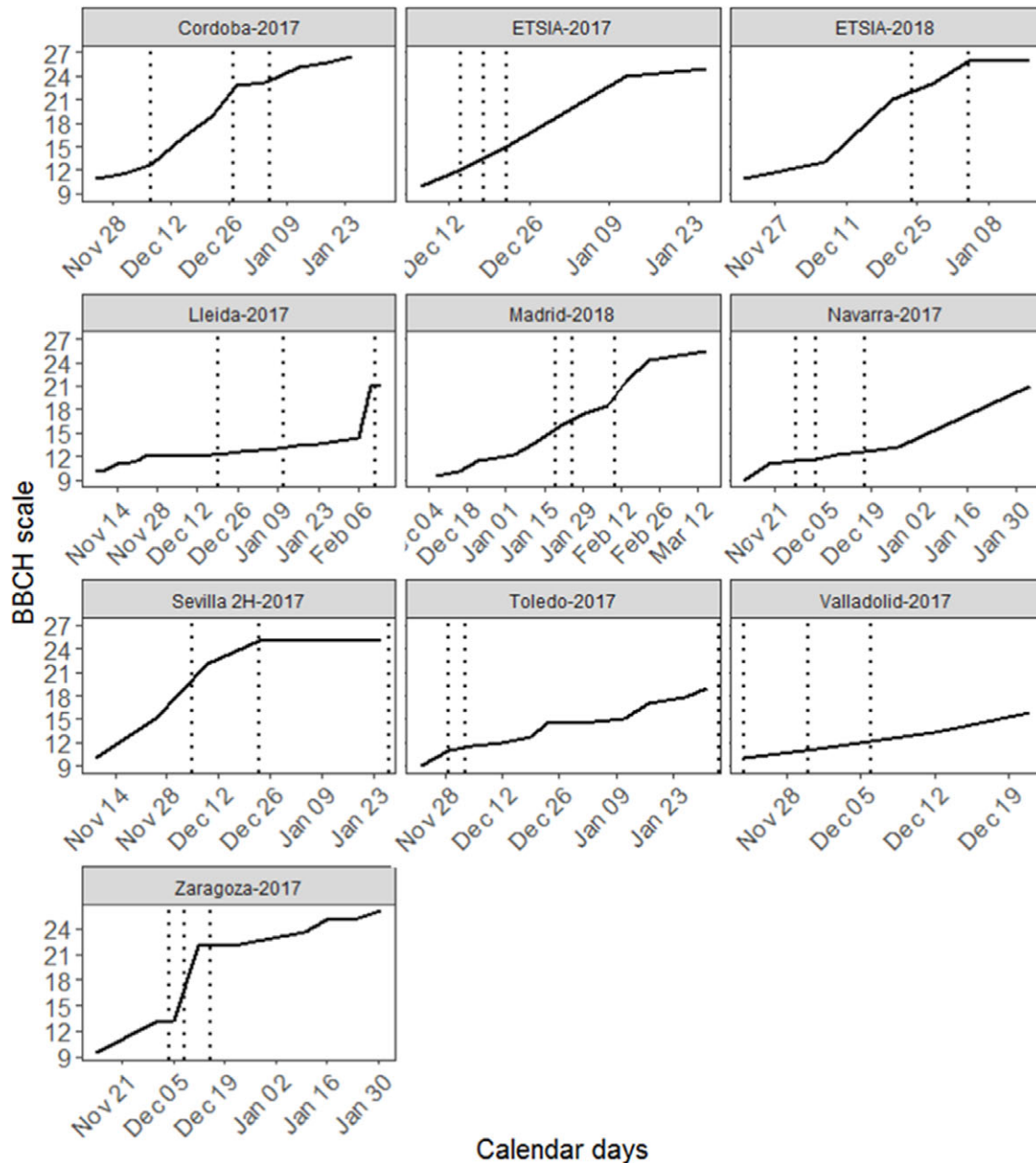


Figure 2. Phenological stages of the first emerged seedlings of *Avena sterilis* ssp. *ludoviciana* using the BBCH scale, during the 2016–2017 season. Vertical dotted lines indicate 70%, 80%, and 90% emergence at each test location.

which agrees with findings reported by Fernández-Quintanilla et al. (1990), who observed that under controlled conditions, a higher proportion of *A. sterilis* seeds germinated when average temperatures were below 10 C than when temperatures were above 10 C and that germination was severely reduced with temperatures above 30 C. In the second growing season, emergence was greatest at Sevilla 2H (50.0%) compared with all other locations (7.3% to 26.5%) (Table 5).

Emergence of *A. sterilis* most frequently occurred between November and February after a daily average temperature below 9 C occurred, similar to what was observed by Aibar et al. (1991). In Zaragoza in 2017 to 2018, the dry autumn delayed the onset of emergence until February. At northern locations, most seedlings

emerged in a main flush during this period; in contrast, at southern locations (Sevilla and Córdoba) during both seasons and in Lleida in 2016 to 2017, two flushes were observed; a larger flush occurred between November and January and a smaller flush occurred at the end of February. The lack of precipitation in midwinter (January and February) may have prevented seedlings from emerging in these locations.

Phenology and Early Growth

In the southern locations, *A. sterilis* reached the tillering stage between November 25 and the end of December, from 48 to 79 d after sowing. In the northern locations, this stage occurred later,

Table 6. Root mean-square error (RMSE) values obtained from thermal (TT) and hydrothermal (HTT) time of models developed by Leguizamón et al. (2005) compared with those of the new model at each experimental site during seasons 2016 to 2017 and 2017 to 2018.^a

Location	Season	Leguizamón et al. (2005)		New model	
		TT	HTT	TT	HTT
Córdoba	2016–2017	37.4	43.0	13.2	7.8
Córdoba	2017–2018	18.6	25.4	22.1	21.6
Lleida	2016–2017	30.5	42.5	9.6	9.0
Lleida	2017–2018	47.8	58.8	38.2	10.0
Madrid	2016–2017	15.4	30.2	6.1	6.4
Madrid	2017–2018	22.3	10.8	13.3	20.5
Pamplona	2016–2017	13.6	17.0	7.7	5.4
Pamplona	2017–2018	37.6	47.1	10.7	7.2
Sevilla 2H	2016–2017	38.4	49.5	9.0	5.6
Sevilla 2H	2017–2018	40.1	47.5	11.5	15.0
Sevilla ETSIA	2016–2017	53.2	61.4	13.4	13.5
Sevilla ETSIA	2017–2018	23.3	28.4	10.0	12.2
Toledo	2016–2017	15.2	25.2	11.2	14.1
Valladolid	2016–2017	24.1	23.4	16.3	13.7
Zaragoza	2016–2017	51.5	34.7	27.1	14.9
Zaragoza	2017–2018	11.3	25.5	27.4	37.5
Average		30.0	35.7	15.4	13.4

^aBold indicates the lowest RMSE value in each site and season among the four models.

at the end of January (between 102 and 112 d after sowing), with the exception of Zaragoza, where it occurred in mid-December (64 d after sowing). Chemical control methods applied to weeds at early phenological stages result in higher control efficacies than at later stages. This becomes even more evident with herbicide-resistant populations (Moss et al. 2001). For this reason, the parameterization of our results can help determine these application timings. The relationship of the seedling emergence pattern with the phenological stage demonstrates that the best time to perform a chemical control in southern locations is when the emergence percentages rise to about 70% of total emergence. Tillering of the first *A. sterilis* seedlings starts when 80% of seedlings have emerged, and these more advanced individuals could escape control by herbicides. On the other hand, in northern locations, the best timing for chemical control would be when 80% of total seedling emergence is achieved, because phenological development is slower due to colder temperatures, and tillering is delayed, allowing for control of a higher percentage of emerged weeds (Figure 2).

Accuracy of the Previously Published and New Models

The Weibull function, with an average RMSE value of 11.8, described the *A. sterilis* emergence slightly better than the Gompertz (RMSE = 11.9) or log-logistic (RMSE = 12.3) equations. For the TT model, the parameter values were established at 8.50 for k and 1.54 for b ; while the parameters for the HTT model were set at 7.44 and 1.51 for k and b , respectively. The biological parameters to calculate the TT and HTT used in the new models were -1.0 , 6.6 , and 18.0 C for T_b , T_o , and T_c , respectively, while the Ψ_b was established at -0.2 MPa. The T_b obtained in this experiment is close to the -0.8 C established by Fernández-Quintanilla et al. (1990) under growth chamber conditions. However, substantial differences were found for T_o and T_c , which were lower than those established in growth chamber experiments by Fernández-Quintanilla et al. (1990)

and by Üremiş and Uygur (1999), which set them at 10 and 30 C, respectively. On the other hand, with a Ψ_b of -0.2 MPa *A. sterilis* showed higher dependence on soil moisture than other winter weeds, such as ripgut brome (*Bromus diandrus* Roth) (-1.3 MPa) or *C. diluta* (-0.5 MPa) (García et al. 2013; Sousa-Ortega et al. 2020b). Moreover, the established Ψ_b in the new model is considerably high compared with that obtained by Fernández-Quintanilla et al. (1990), who established it at -1.2 MPa.

The new model, with average RMSE values across locations of 15.4 and 13.4 for TT and HTT models, was more accurate than the model developed by Leguizamón et al. (2005) (Table 6; Figures 3 and 4). The new model (TT or HTT) showed higher accuracy (lowest RMSE values) in 13 of 16 environments (site and season) compared with the previous model (Table 6). In contrast, the fit for the Leguizamón et al. (2005) models was worse than expected, having an average RMSE value of 30.0 for the TT model, with only two locations having an RMSE less than 15. The fit for the HTT was even poorer, with an average RMSE value of 35.7 and one only location where RMSE was less than 15. Inclusion of soil moisture data did not improve the accuracy of the model from Leguizamón et al. (2005), but it did improve the accuracy of the newly developed model. The average RMSE was reduced by two points, and the sites showing very good accuracy (RMSE = 5 to 10) increased from five to seven, the number of sites with good accuracy (RMSE = 10 to 15) was maintained, and the number of sites with unsuccessful accuracy (RMSE >15) was reduced from five to three. Greatest accuracy improvement due to the inclusion of soil moisture was observed in Lleida 2017 to 2018 and Zaragoza 2016 to 2017, where RMSE was reduced from 38.2 and 27.1 to 10.0 and 14.9, respectively. The HTT model successfully described the emergence pattern of *A. sterilis* at all locations, with the exception of the 2017 to 2018 locations in Córdoba, Madrid, and Zaragoza (Table 6; Figures 3 and 4). The lack of accuracy was especially relevant at Zaragoza, where the model obtained an RMSE value of 37.5 (Table 4). These results may be explained due to bad setting of the starting point for TT and HTT accumulation. Despite the fact that the first relevant rainfall was registered on January 6, the availability of water by the seeds was delayed for 3 wk until the temperatures were above 0 C, because the water reserves were frozen. If this moment is taken as the starting point, the accuracy of the new model increases from 27.4 and 37.5 RMSE values to 9.6 and 9.2 for TT and HTT, respectively. In addition, the model developed by Leguizamón et al. (2005) had a similar response, dropping from 11.3 to 5.3 for the TT model and from 25.5 to 9.2 for the HTT model.

Data Validation with Independent Data

The improvements in accuracy occurring with the new models were expected, as these models were developed using the data collected for this experiment. For this reason, to perform a fair comparison, the models were subjected to independent data.

Weather conditions between November and April at the experimental sites used for data validation, Tomejil and Sevilla ETSIA, ranged from 17.6 to 20 C for the hottest monthly temperatures and 7.1 to 9.6 C for the coldest monthly temperatures during the 3 yr. On the other hand, precipitation during 2005 to 2006 and 2006 to 2007 was a typical rainfall distribution occurring under Mediterranean environments, with precipitation mainly occurring during autumn (Romero et al. 1998), while autumn in 2007 to 2008

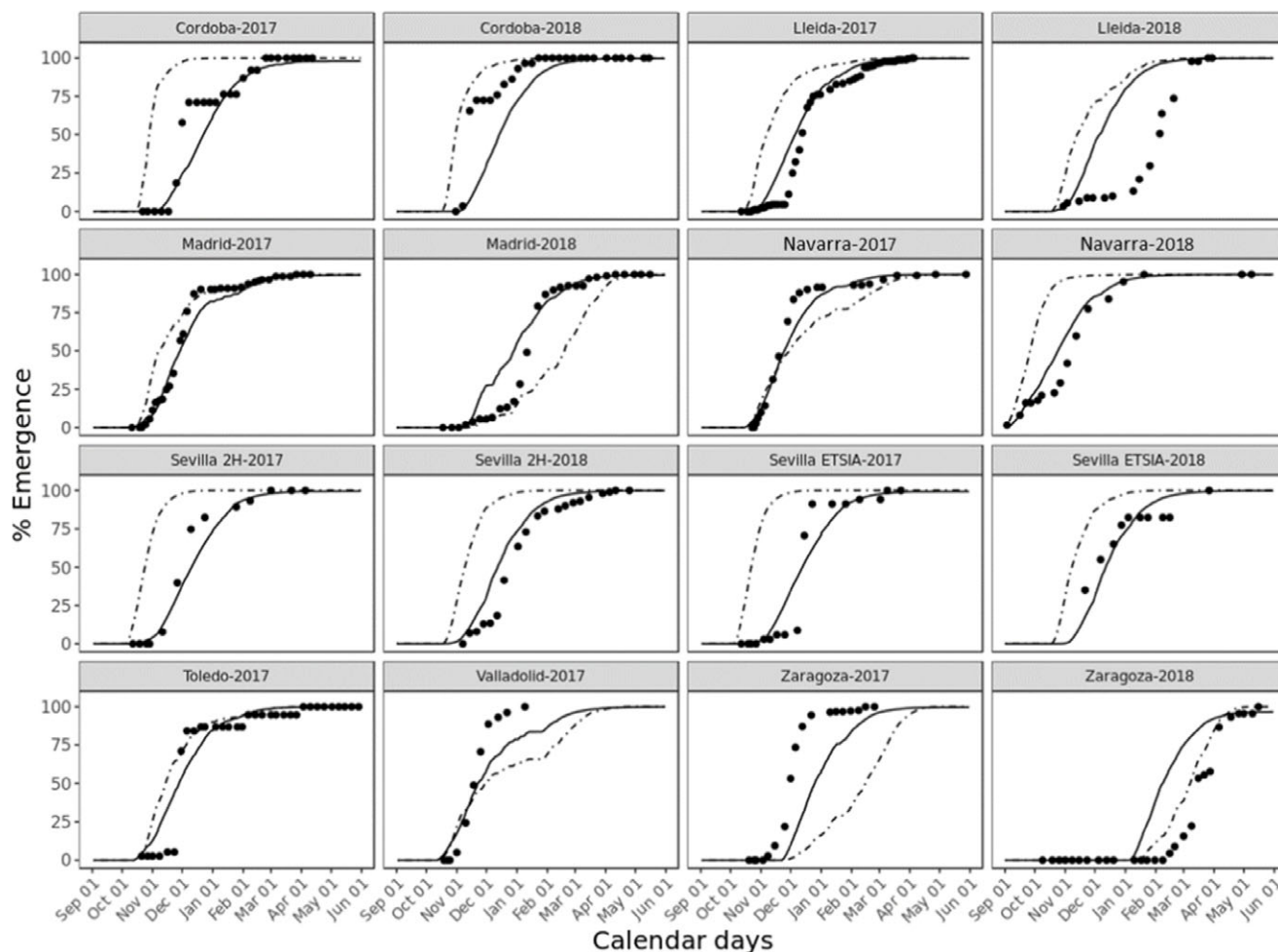


Figure 3. Predicted emergence of *Avena sterilis* ssp. *ludoviciana* grown in 16 environments using the thermal model designed by Leguizamón et al. (2005) [$Y = 100\{1 - \exp[-\log(2) * (TT/344.3)^{2.09}]\}$] (dotted line) and the new thermal time model [$Y = 100\{1 - \exp[-\exp(-8.50)(TT)^{1.54}]\}$] (solid line). Observed seedling emergence is shown by the black dots.

was very dry, almost without any rainfall from October until February (Table 7).

Again, the new models improved the accuracy of the emergence description compared with those obtained using the Leguizamón et al. (2005) models (Table 8; Figures 5 and 6). In this validation process, the new model (TT or HTT) showed the lowest RMSE values in five out of eight experimental conditions (site and season) compared with the older model (Table 8). The RMSE averaged 16.3 and 18.0, respectively, for the new TT and HTT models, while these values were higher (24.9 and 23.9) for the Leguizamón et al. (2005) models. However, in this case, the HTT model did not improve the accuracy of the TT. These results could be explained by the dry autumn that occurred at Tomejil and Sevilla ETSIA in 2008, which would have prevented the HTT model from achieving 100% emergence. Maybe the observed emergence was not the full emergence, as it would be if there had been not moisture limitation, as the HTT model suggested. In contrast, the HTT model worked better in 2005 to 2006, when it improved the prediction from 11.1 to 6.7 (Table 8; Figures 5 and 6).

Based on the equations of the newly developed models, the inclusion of a T_c and a reduction of the period between T_0 and T_c was required for the improvement of the emergence models

of this species. Similar results were observed for *L. rigidum* (Sousa-Ortega et al. 2020a) and *C. diluta* (Sousa-Ortega et al. 2020b), which demonstrates there is potential for improving the accuracy of the models in future research.

The emergence of *A. sterilis* has effectively been described with a wide experiment including nine locations, developed and evaluated in 16 environments, and validated under 8 additional environments. Overall, the mean seedbank emergence for all environments was 30% during the first season and 21% during the second season (Table 5). In both seasons, the main emergence flush occurred between November and February. According to the phenological stage, *A. sterilis* achieved tillering earlier in southern sites, between November 25 and the end of December, whereas this stage was reached at the end of January in northern sites. We proposed therefore propose that chemical control methods should be applied when cumulated emergence is 70% (158 hydrothermal degrees) in southern locations and 80% (192 hydrothermal degrees) in northern locations. The new model (TT and HTT) was found to be more accurate than the previously published model, showing higher accuracies in 18 out of 24 scenarios. Moreover, it demonstrated the need of including a T_c , which avoids DTD accumulation when the temperature is above 18 C, for modeling the emergence of

Table 7. Average monthly temperature and rainfall accumulation at the independent locations during the seasons 2005–2006, 2006–2007, and 2007–2008.

Site	Month	Temperature			Rainfall accumulation		
		2005–2006	2006–2007	2007–2008	2005–2006	2006–2007	2007–2008
		C			mm		
Sevilla ETSIA	October	17.7	19.6	18.8	119.2	197.8	22.6
Sevilla ETSIA	November	11.5	14.3	13.1	25.4	120.6	91.4
Sevilla ETSIA	December	9.7	8.9	9.6	29	43.4	15
Sevilla ETSIA	January	7.1	8.2	10.8	38	30.4	44.8
Sevilla ETSIA	February	9.1	11.8	13.4	52.8	59.6	68.4
Sevilla ETSIA	March	13.4	13.4	14.1	63.6	12.4	20
Sevilla ETSIA	April	17	15.3	16.8	35.2	38	165.4
Average/total		13.5	14.4	14.9	363.2	539.2	470.4
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	13.6		58	65
Tomejil	March		12	13		20.6	25.8
Tomejil	April		14.3	16		43.2	177.6
Average/total			14.5	14.9		430.2	531.0

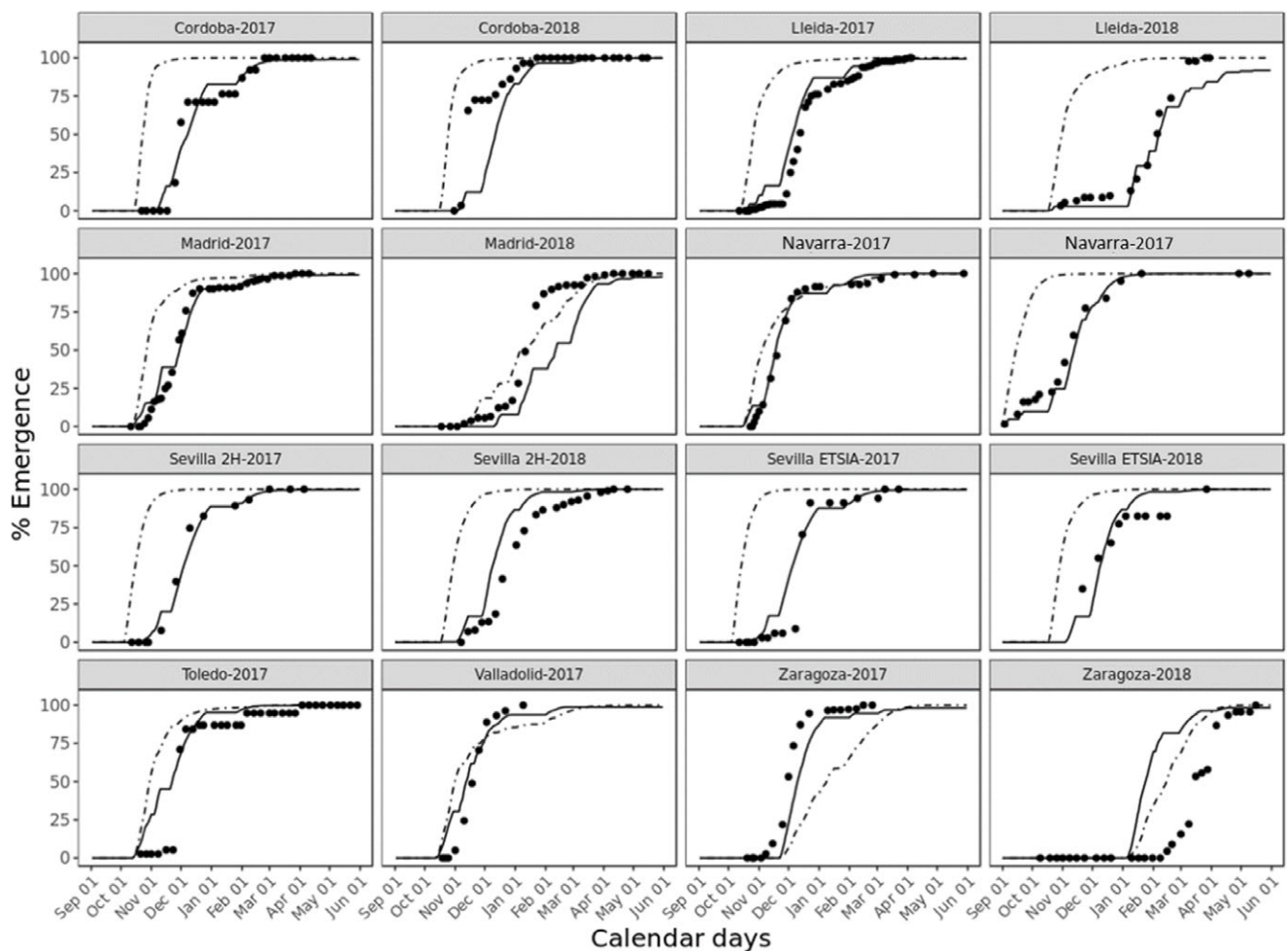


Figure 4. Predicted emergence of *Avena sterilis* ssp. *ludoviciana* grown in 16 environments using the hydrothermal model designed by Leguizamón et al. (2005) [$Y = 100[1 - \exp\{-\log(2) \cdot (\text{HTT}/207.7)^{1.53}\}]$] (dotted line) and the new hydrothermal time model [$Y = 100[1 - \exp\{-\exp(-7.44)(\text{HTT})^{1.51}\}]$] (solid line). Observed seedling emergence is shown by the black dots.

Table 8. Root mean-square error (RMSE) values obtained from thermal (TT) and hydrothermal (HTT) time of models developed by Leguizamón et al. (2005) compared with those of the new model for independent data collected at eight environments.^a

Location	Sowing	Leguizamón et al. (2005)		New model	
		TT	HTT	TT	HTT
Sevilla ETSIA	S06YR06	13.8	27.2	11.1	6.7
Sevilla ETSIA	S06YR07	41.9	41.9	6.0	5.4
Sevilla ETSIA	S07YR07	13.6	10.3	17.6	12.9
Sevilla ETSIA	S07YR08	29.6	29.6	11.1	21.8
Sevilla ETSIA	S08YR08	30.3	17.5	35.1	36.7
Tomejil	S07YR07	16.5	23.9	6.4	11.7
Tomejil	S07YR08	26.1	23.0	9.3	17.9
Tomejil	S08YR08	27.1	17.3	34.0	31.1
Average		24.9	23.9	16.3	18.0

^aSee Table 2 for explanation of location and sowing codes. Bold indicates the lowest RMSE value in each site and season among the four models.

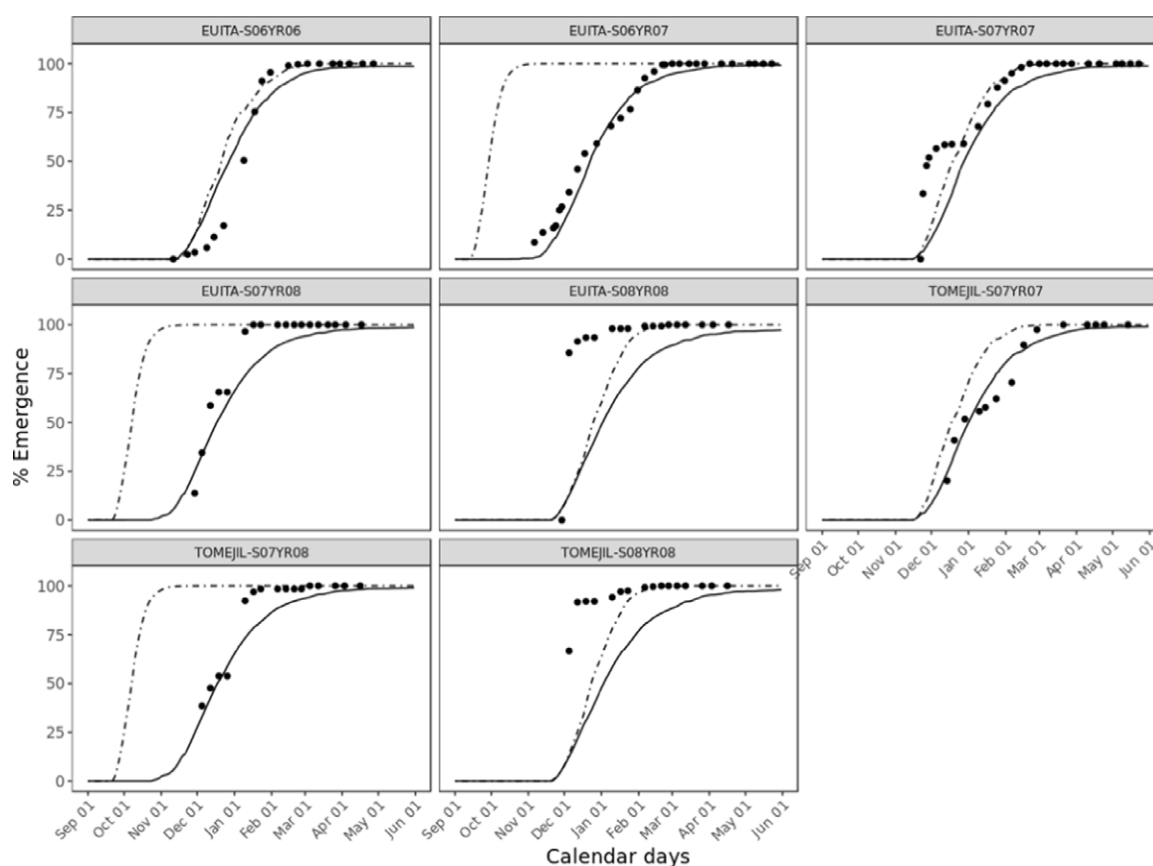


Figure 5. Predicted emergence of *Avena sterilis* ssp. *ludoviciana* based on independent data from eight environments using new thermal time model [$Y = 100[1 - \exp[-\exp(-8.50)(TT)^{1.54}]]$] (solid line) and the thermal model designed by Leguizamón et al. (2005) [$Y = 100[1 - \exp[-\log(2) * (TT/344.3)^{2.09}]]$] (dotted line). Observed seedling emergence is shown by the black dots.

this weed. According to Royo-Esnal et al. (2010), who indicated that a model presents a good predictive capability when the RMSE is lower than 15, the new HTT model described with good precision the emergence of *A. sterilis* in 18 of 24 environments, including four independent experiments, and failure occurred only in very dry seasons, when the TT model was more accurate. Improvements in understanding this behavior under low moisture conditions is needed to improve understanding of the emergence

biology of *A. sterilis*. Moreover, the lack of a successful description in six environments suggests the need to continue to adjust these models to achieve satisfactory results at more sites.

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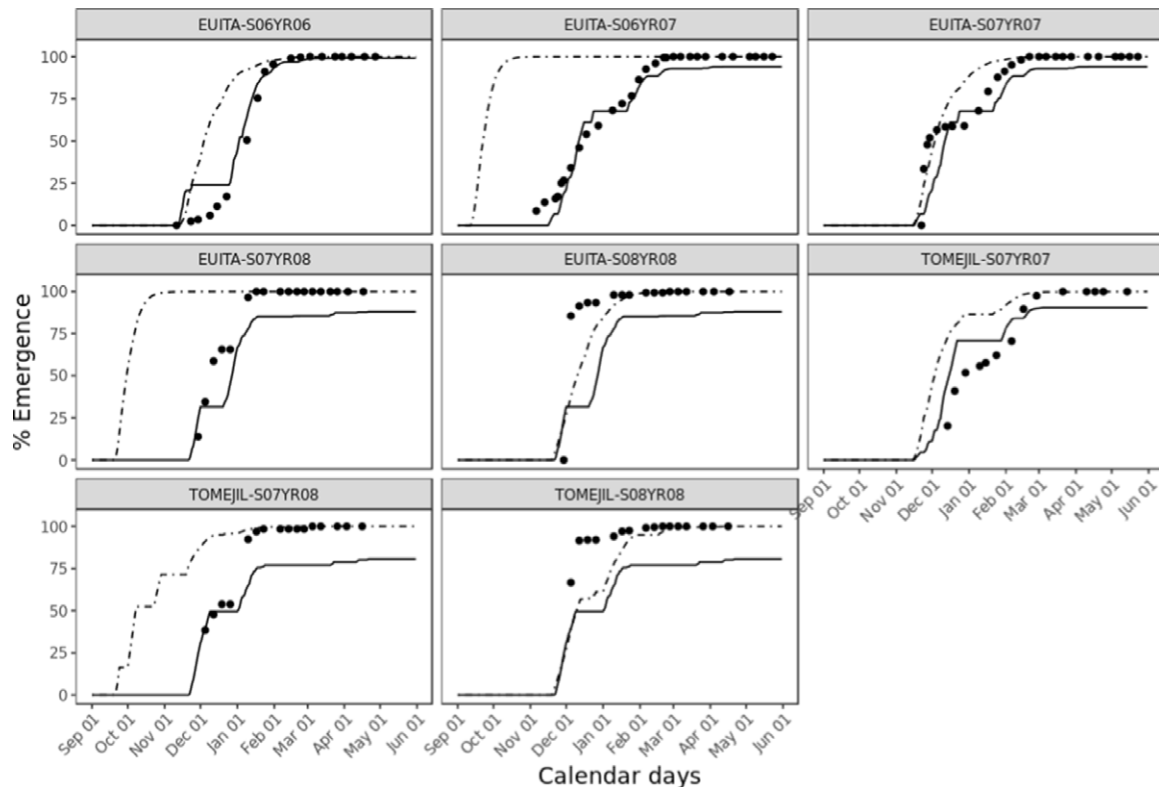


Figure 6. Predicted emergence of *Avena sterilis* ssp. *ludoviciana* based on independent data from eight environments using new hydrothermal time model [$Y = 100\{1 - \exp[-\exp(-7.44)(HTT)^{1.53}]\}$] (solid line) and the hydrothermal model designed by Leguizamón et al. (2005) [$Y = 100\{1 - \exp[-\log(2) * (HTT/207.7)^{1.53}]\}$] (dotted line). Observed seedling emergence is shown by the black dots.

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