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Running title: *Centaurea diluta* emergence

## **Modeling the Emergence of North African Knapweed (*Centaurea diluta*), an**

### **Increasingly Troublesome Weed in Spain**

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## Abstract

North African knapweed (*Centaurea diluta* Aiton) is an annual weed that is widespread in southern Spain and is of increasing concern in dryland cropping systems. Despite its expanding range in Spain, there is limited information on the emergence timing and pattern of this species, which is critical for developing more timely and effective management strategies. Therefore, there is a need to develop simple and reliable models to predict the timing and emergence of this annual weed under dryland conditions. A multi-location field experiment was established across Spain in 2016-2017 to assess the emergence of *C. diluta*. At each of 11 locations, seeds were sown in the fall, and emergence was recorded. Overall emergence averaged 39% in the first year across all sites and 11% in the second year. In both years, the main emergence flush occurred at beginning of the growing season. The three-parameter Weibull function best described seedling emergence of *C. diluta*. Emergence models were developed based on thermal time (TT) and hydrothermal time (HTT) and showed high predictability, as evidenced by root mean square error prediction (RMSEP) values of 10.8 and 10.7, respectively. The three cardinal points were established for TT and HHT at 0.5 °C, 10 °C and 35 °C for base, optimal and ceiling temperature, while base water potential was estimated at -0.5MPa.

**Keywords:** Hydrothermal model, North African knapweed, RMSEP, seedling emergence model, thermal model, Weibull.

## Introduction

In recent years, legislation in the European Union has restricted the number and use of herbicides in cropping systems (Barzman and Dachbrodt-Saaydeh 2011; European Council 1991; European Parliament 2009) as well as tillage frequency (Kutter et al. 2011), thus limiting weed control options for growers. These restrictions have made it more difficult to control troublesome weeds and led to an increase in the occurrence of lesser known weeds, such as North African knapweed (*Centaurea diluta* Aiton) in southern Spain.

*Centaurea* is a genus in Asteraceae that has a worldwide distribution and is comprised of a diverse group of about 250 species (Susanna and Garcia-Jacas 2007). Some of the species, such as red star-thistle (*Centaurea calcitrapa* L.) and Iberian knapweed (*Centaurea iberica* Trevir. ex Spreng.) (Nosratti et al. 2017) are considered troublesome weeds, while others including diffuse knapweed (*Centaurea diffusa* Lam.) and Maltese star-thistle (*Centaurea melitensis* L.) are of minor agronomic importance. Some *Centaurea* species have also evolved resistance to several herbicide families including yellow star-thistle (*Centaurea solstitialis* L.) to acetolactate synthase (ALS) inhibitors in the U.S., spotted knapweed (*Centaurea stoebe* subsp. *australis* Pančić ex A.Kern.) Greuter to synthetic auxins in Canada, and garden cornflower (*Centaurea cyanus* L.) populations in Poland to both herbicide families (Heap 2018).

A total of 94 *Centaurea* species have been described in the Iberian Peninsula (Valdes et al. 1987) including the increasingly troublesome annual herb, *C. diluta*. This species is becoming a major agronomic weed primarily because of its large size and high competitive ability (Saavedra et al. 2018). In recent years, it has spread into southern Spain and is of increasing concern to farmers in the region (Ortiz et al. 2015). The first reference to this species as a weed was in the early 1980s when it was found in wheat, sunflower, pea, and

beet fields (Castroviejo et al. 1980; Pujadas-Salvá and Hernández-Bermejo 1986; Saavedra 1997). Since then, its importance has increased largely because its seeds can easily contaminate cereal grains at harvest and can also be mistakenly seeded with cereal grains at planting. These dispersal pathways (Domínguez-Borrero et al. 2015) may explain its irregular distribution in the region (Vázquez and Guerra 2008).

*Centaurea diluta* is an annual dicot native to North Africa and southwestern Europe including Spain. It is a vigorous plant that can reach up to 350 cm in height and produce a large number of capitula and hairy achenes (3 mm) that can be easily dispersed (Saavedra 1997; Valdes et al. 1987). To our knowledge, there are no published data on the number of seeds produced by *C. diluta* plants or their dormancy status. But stands of similar annual herb congeners such as *C. solstitialis* can produce nearly 28,000 seeds m<sup>-2</sup> (Gutierrez et al. 2005). Anecdotal reports and studies from similar species suggest that seeds of *C. diluta* exhibit limited dormancy (Joley et al. 1997, 2003)

There is also relatively little published information on methods for controlling *C. diluta*, except for several technical reports (Saavedra et al. 2017, 2018). The availability of such information is critical for the development of integrated weed management (IWM) programs for this species. To develop and implement effective management strategies, a better understanding of its seedling emergence pattern and our ability to accurately predict emergence and growth are required.

Seed germination is largely dependent on three key biological parameters related with temperature (Bradford 2002). The first is the base temperature ( $T_b$ ), which is the minimum temperature for a seed of a given species to germinate such that thermal degrees are not accumulated below this temperature; second is the ceiling temperature ( $T_c$ ), which is the maximum temperature for germination, such that no thermal degrees above this temperature

are accumulated; and third, optimum temperature ( $T_o$ ), which is the temperature at which seed germination occurs most rapidly. These parameters aid in estimating the thermal time (TT) and the hydrothermal time (HTT) for describing the emergence pattern of weeds. Thermal time models only use soil temperature to describe emergence, while HTT models correct TT accumulating degrees when soil moisture is above a base level (Grundy 2003). In dryland cropping systems, HTT-based models are more precise than TT models because they also consider the water content of soils (Royo-Esnal et al. 2012). However, accurately determining soil moisture within a field can be difficult because many soil properties can vary widely within a single field (Finch-Savage 2004). For this reason, TT-based models with good accuracy may be more practical and useful. The ability to accurately predict the emergence pattern of a target weed or weeds can be valuable to crop managers because it allows them to implement control tactics at the most appropriate time when weeds may be most vulnerable (Barros and Freixial 2010; Kropff and Spitters 1991; Zimdahl 2007). Increasing the efficacy of a given weed control strategy is likely to also result in improved economic and environmental outcomes as lower quantities of herbicide or cultivations are needed to achieve the same level of control than later applications or cultivations when plants may be larger and more difficult to control (Shaner and Beckie 2014).

Thermal time has been widely used to develop emergence predictive models for a number of weed species. In Spain, the emergence patterns of some of the most problematic weeds in dryland cereals have been modeled and shown to have fair accuracy, including sterile oat (*Avena sterilis* L.) (Leguizamón et al. 2005), rigid ryegrass (*Lolium rigidum* Gaudin) (Izquierdo et al. 2013, Sousa-Ortega et al. 2019), ripgut brome (*Bromus diandrus* Roth) (García et al. 2013), corn poppy (*Papaver rhoeas* L.) (Izquierdo et al. 2009), and prostrate knotweed (*Polygonum aviculare* L.) (Royo-Esnal et al. 2015).

Certainly, knowledge of the phenological stages of target weeds is essential for implementing appropriate management tactics, particularly during early growth, as it can facilitate determining the critical period of weed control (Knezevic and Datta 2015), the most effective method of control (Royo-Esnal et al. 2012), and also potentially provides important information on whether a given species may be adapted to a particular habitat or region (Holt 1991).

Until recently, *C. diluta* was not considered a major agronomic weed in Spain and as such no research has been performed to determine or predict its emergence pattern. However, the increasing importance of this weed in southern Spain, and the possibility of invasion into northern Spain as climate changes, makes *C. diluta* an important weed species to target for further study. Thus, the objective of this research was to develop a model to predict the emergence pattern of *C. diluta* and describe its early growth stages under Mediterranean semi-arid conditions. This research is critical because the ability of this species to expand its range into new regions will depend largely on the likelihood of its seeds to germinate and its seedlings to emerge and establish in these novel environments.

## Material and Methods

**Plant Material.** Seeds of *C. diluta* were collected from more than 20 individual plants in June 2016 in Los Molares, Sevilla, in southern Spain (37°09' N, 5°43' W) from a commercial wheat field. Seeds were cleaned and dry-stored in a refrigerator at 4 C until needed for field trials in September 2016.

**Experimental Design.** The experiment was established in 2016-17 in 11 locations across Spain (Figure 1), and in seven of the locations, *C. diluta* emergence was monitored both in 2016-17 and for a second season in 2017-18 (Table 1). The experiment was conducted under

rain-fed conditions with no supplemental irrigation similar to conditions in cereal fields where this weed species is problematic. Four 0.25 by 0.25 m quadrats were established as experimental replications in each location. In each quadrat, a total of 100 *C. diluta* seeds were sown in the top 2 cm of soil by gently mixing the soil. The same sowing procedure was followed in all locations, except at the Sevilla Garden site, where the experiment was conducted using 35 L pots containing a mixture of 50% sand and 50% peat moss. Seeds were only sown during the first season between October and November 2016, depending on field and weather conditions (Table 1). Seedling emergence in each quadrat was recorded weekly from October until May, except during emergence flushes when data were collected every 2-3 days. In three northern sites and three southern sites during the first year, the first two seedlings to emerge from each replicate quadrat were recorded and allowed to grow until mid-February to assess establishment success and early growth under the different environmental conditions. All other seedlings that emerged at these six sites as well as all seedlings emerging at the other six sites were recorded and removed from quadrats at each sampling. The BBCH Scale (Meier 2001) was used to assess seedling phenology for the two plants per quadrat that were allowed to grow. In each location, a temperature and conductivity data logger (digital thermometer DS18B20 and analogic conductivity sensor LM393-N) were placed at a 2 cm soil depth within the experimental area.

**Estimation of Thermal and Hydrothermal Time.** Temperature and moisture data from each location were used to estimate cardinal temperatures: base ( $T_b$ ), optimum ( $T_o$ ) and ceiling ( $T_c$ ). These values were obtained through an iterative process using the following steps: several combinations of these three cardinal temperatures were used to develop the TT or HTT; afterwards, a non-linear regression between TT or HTT and observed data (field emergence data) was tested using three biological growth equations [1-3]; finally the best-fitted combination for the initial parameters was selected. Base water potential ( $\Psi_b$ ) was

calculated using a similar procedure. In the first year, the sowing date was considered as the zero moment while in the second year, the zero moment was considered the first day when >10 mm of rain were received.

Water content was estimated using conductivity values given the high correlation between these two variables (Brevik and Fenton 2002). Then, water content was used to calculate the water potential following the equations described in Saxton and Rawls (2006).

Once the cardinal temperatures were fixed, both cumulative thermal (TT) and hydrothermal time (HTT) were calculated by summing the daily TT and HTT as follows:

$$\text{If the soil temperature was between } T_b \text{ and } T_o: \quad TT = T - T_b$$

$$\text{If the soil temperature was between } T_o \text{ and } T_c: \quad TT = (T_c - T)$$

$$\text{and if } T < T_b \text{ or } T > T_c, \text{ then } TT = 0$$

where  $T$  is the mean daily temperature.

Hydrothermal time was estimated by including soil moisture in the TT calculations.

$$HTT = TT * (\Psi - \Psi_b)$$

where  $(\Psi - \Psi_b) = 0$  if  $\Psi < \Psi_b$ , otherwise,  $(\Psi - \Psi_b) = 1$ .

To develop this TT, a reduction in daily TT was established when the temperature was above the  $T_o$  because a slight reduction between  $T_o$  and  $T_c$  makes more biological sense than a drastic reduction when the temperature is above  $T_c$ . This approach to determining TT was used by Roman et al. (2000) and Sousa-Ortega et al. (2019) with good results. Moreover, as the three cardinal points were established by an iterative process using numerous combinations of them, a possible result with similar  $T_o$  and  $T_c$  would suggest that this slight reduction in TT is not necessary.



**Modelling Seedling Emergence and Statistical Analysis.** Three sigmoidal models were fitted to the results: Gompertz [1], three-parameter Log-logistic [2], and three-parameter Weibull [3] (Ritz et al. 2015):

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

where  $Y$  is the cumulative emergence,  $b$  is the emergence rate,  $TT$  is the thermal time (HTT if using this scale), and  $m$  is the inflection point, which is the time to reach 50% emergence (Onofri et al. 2010).

$$Y = d / (1 + e^{(b * (\log TT - \log(m)))} \quad [2]$$

$$Y = d * e^{(-e^{(b(\log(TT) - \log(m)))} \quad [3]$$

where  $Y$  is the cumulative emergence,  $d$  is the maximum emergence,  $b$  is the slope (emergence rate) at  $m$ , and  $m$  is the inflexion point.

The accuracy of these models was tested with the root mean square error prediction (RMSEP) [4], where greater model accuracy is indicated by lower RMSEP values (Izquierdo et al. 2013).

$$RMSEP = \sqrt{1/n \sum_{i=0}^n (x_i - y_i)^2} \quad [4]$$

where  $x_i$  represents the actual cumulative percentage emergence,  $y_i$  is the predicted cumulative percentage emergence, and  $n$  is the number of observations. Testing was performed for 13 of 18 data sets because data from sites with low emergence percentages (<10%) were excluded as they were considered not representative of the emergence behavior of this species (Guillemin et al. 2013).

**Practical Use of the Model.** The model selected was tested with independent data to evaluate its predictive ability. The independent validation was conducted in two additional

experiments. The first of these experiments was carried out in Morón (37°15'41.3" N, 5°44'50.4" W) following the same procedure described above and sowing *C. diluta* seeds on December 17, 2018. The soil was a sandy-loam (68% sand, 14% silt and 18% clay) and weather data were recorded with the same data logger described above. In the second experiment, the model was fitted to a natural seed bank of *C. diluta* in Montoro (38°00'23" N, 4°24'34" W) in 2019/2020. The soil at this site was a clay composed of 5% sand, 31% silt, and 62% clay. Weather data were collected from the nearest weather station (Adamuz) and water content was estimated using the equations described in Fuentes-Yaguë (1998).

To further evaluate the accuracy of the model under different weather conditions, temperature and rainfall data for two seasons from the past 10 years at the Cordoba site were selected to run the model. The weather data were taken from a weather station (37°51'32.1" N, 4°48'03.3" W) adjacent to the Cordoba experimental site. The first season was selected because of an early first rain event (Sept 8, 2013), while the second season was selected for its relatively late first rain event (Oct 27, 2011). A linear regression based on experimental years was used to estimate the soil temperature for these two seasons.

**Statistical Analysis.** Differences in total seedling emergence among locations were analyzed by one-way ANOVA for each season. Differences among means were determined using Tukey's test at  $P = 0.05$ .

## Results and Discussion

**Weather Conditions.** Weather conditions differed substantially between locations and seasons. These differences should provide robustness to any mathematical model, which fits the emergence pattern. According to the model, moisture levels were adequate for the

accumulation of hydrothermal degrees in all cases, with the exception of Sevilla ETSIA (both years), Sevilla FTS, and Valladolid (Figure 2).

**Emergence Pattern.** During the first season, the average percentage of emergence among all locations was of 38.9% (Table 2), with significant differences between locations ( $P < 0.0001$ ). Emergence of *C. diluta* was higher (52-63%) in Valladolid, Sevilla Garden, Madrid, Zaragoza and Sevilla 2H than in Barcelona, Sevilla FTS and Toledo. The average percentage of *C. diluta* emergence based on all locations during the first year was lower than that reported for other *Centaurea* species. The highest emergence values of 52-63% are below emergence values reported for other *Centaurea* species, including *C. cyanus* (68-79%) (Guillemin et al. 2017) and *C. iberica* (>75%) (Nosratti et al. 2017). However, these latter studies were conducted under controlled environmental conditions and under more ideal germination and emergence conditions than likely occurred under the variable field conditions in our study.

During the second season, the average total emergence (11%) at the seven sites where data were collected was lower than during the first year. Significant differences in total emergence were only found between the Cordoba and Madrid locations ( $P$ -value  $< 0.031$ ) (Table 2). An average 48.2% of *C. diluta* seeds sown in this study did not result in the production of seedlings. The percentage of seeds not producing seedlings ranged between 39.3% and 71.3% depending on location. This trend of decreasing seedling emergence (Table 2) was also observed in *C. cyanus* for which seed viability was found to decrease at the end of the first year (Guillemin et al. 2017). Although the fate of seedlings that did not emerge (i.e. seeds remained dormant in the soil, died, or were predated) was not determined. The emergence observed during the second season was on average less than one third (11%) of that in the first year (39%), and this tendency is likely to continue in the forthcoming seasons;

thus, if the seed rain of *C. diluta* can be curtailed during two seasons, the seed bank of this species is likely to be substantially reduced. Certainly a more in depth understanding of the fate and viability of *C. diluta* seeds in the soil would be most valuable for accurately assessing the soil seed bank and resulting seedling emergence levels.

The emergence pattern of *C. diluta* in 2016-17 was similar in all locations, with a single main flush (50% of the emergence) occurring within 20 days of sowing (DAS), except at the Toledo site, where a drastically different emergence pattern was observed. The low proportion of seedlings emerging at this site (8.8%, Table 2), may not be representative of the typical emergence levels for this species (Guillemin et al. 2013). In general, emergence patterns across experimental locations were similar for the first 13 DAS, but differences were observed after 75% emergence was achieved.

*Centaurea diluta* emergence flushes occurred early in the season and were concentrated over a few days (Figures 3 and 4). Thus, control of these seedlings is likely to be easier and more effective at these early growth stages than later stages (Cardina et al. 2007). Moreover, this timing is also likely to be more cost effective since 80-90% of the weed management effort in this region occurs early in the growing season.

**Early Plant Growth.** Interestingly, emergence levels of *C. diluta* were not only similar for the northern and southern locations of Spain (Table 2), but plants survived the relatively cooler winter conditions at the northern sites. *Centaurea diluta* plants survived winter conditions in all locations where early seedling growth was monitored (i.e., three northern and three southern sites). Seedlings of *C. diluta* which emerged between the end of October and beginning of November produced more than 9 leaves (BBCH scale = 19) by mid-February with the exception of the Zaragoza site where temperatures were lower, reducing the growth of plants (Figure 5). The lowest month mean temperature that *C. diluta* was able

to survive was 6.2 C recorded at the Zaragoza site in December (Supplementary data). Hence, *C. diluta* has the potential to establish and possibly become a problematic weed in northern regions of Spain.

**Development and Accuracy of Emergence Model.**  $T_b$ ,  $T_o$ , and  $T_c$  were established at 0.5 C, 10 C and 35 C for thermal time (TT), while base water potential ( $\Psi_b$ ) was estimated at -0.5MPa, for hydrothermal time (HTT), maintaining the same values for  $T_b$ ,  $T_o$  and  $T_c$  as the TT estimation.

The three-parameter Weibull model best fit and explained the emergence of *C. diluta* and with higher accuracy than the Gompertz or the three-parameter log-logistic models. For the TT model, the parameter values were 98.30 for “d”, -2.08 for “b” and 235.40 for “c”; while the parameter values for the HTT model were: “d” = 98.86, “b” = -1.73 and “m”=189.78. Both TT and HTT had similar RMSEP values when assessed using field emergence observations (Table 3 and Figure 3).

Both the HT and HTT models successfully predicted the emergence patterns across the various field locations in Spain, with variations (RMSEP) ranging from 4.8 to 23.9 for the TT model and from 5.5 to 26.8 for the HTT model, depending on the location. The lack of differences in the accuracy of the TT and HTT models could be explained by the weather conditions, where water stress was only evident in Sevilla and Valladolid (< -0.5 MPa) (Figure 2).

Based on the RMSEP ratings of Royo-Esnal et al. (2010), the TT model developed in our study can be considered excellent for the 2016/17 season at the Madrid and Barcelona sites (RMSEP < 5); very good for the 2016/17 season at the Lleida, Sevilla FTS, Sevilla-Garden and Zaragoza sites and for the 2017/18 season at the Barcelona, Cordoba and Lleida sites (5 < RMSEP < 10); good for the 2016/17 season at the Sevilla ETSIA site (10 < RMSEP

< 15), and poor at the Cordoba, Sevilla 2H and Valladolid sites for the 2016/17 season (RMSEP > 15). As for the HTT model, its fit at the Madrid and Barcelona sites changed in 2016/17 from excellent to very good fit and for the Cordoba and Sevilla 2H sites from a poor to a good fit (Table 3). Seed counting at Valladolid finished earlier, as such, later emergence could not be accounted for which it could reduce the accuracy of the model at this site.

**Practical Use of the Model.** The tested sites showed a different behavior. At the Morón site, where 125 seedlings of *C. diluta* were recorded, TT- and HTT-based models provided very good accuracy (Figure 5A). On the other hand, at the Montoro site, where 525 seedlings were recorded, the accuracy of the TT-based model was poor while that of the HTT-based model provided very good accuracy (Figure 5B). This difference was likely due to the water stress experienced at the Montoro site from October 23 to November 23. The value of the HTT model to accurately predict the emergence of both sown seeds of *C. diluta* and those emerging from the resident seed bank, using the zero moment at the first relevant rain (< 10 mm), is to be highlighted (Figure 5). Moreover, the TT model provided good accuracy of the independent data when moisture was not limiting. This situation becomes important in a typical wet autumn in this region because of the difficulty in measuring soil moisture, a key parameter required for the HTT model (Finch-Savage 2004).

*Centaurea diluta* is a troublesome agronomic weed primarily in the southern region of Spain. For this reason, its emergence pattern at the Córdoba site is considered typical for this weed (Figure 6B). The emergence rate of *C. diluta* was relatively fast, with an important emergence flush occurring at 400 degree-days (Figure 6A). Based on this model, the emergence pattern of this species was highly influenced by the timing of the first rain event (>10 mm). If this rain event occurred at the beginning of September, then 90% emergence was achieved by October 20; whereas if rain is delayed until the end of October, 90%

emergence was achieved by March 26 (Figure 6B). Similarly, Joley et al. (2003) reported that emergence of *C. solstitialis* was promoted by an 11mm rainfall event before typical autumn rainfall.

In both our simulated scenarios, the main seedling emergence flush occurred quickly after the first rainfall. If the first rain event occurs at the beginning of September, *C. diluta* will have attained 95% emergence prior to the typical wheat sowing period in the region (December 1-15). Thus, emergence of the remaining 5% of seedlings may be low enough not to significantly affect wheat yield. This is especially the case in sunflower, which is sown during the second half of February in many regions of Spain and by which time 96% of *C. diluta* seedlings would have emerged. If the rain event is delayed until the end of October, emergence was more staggered, attaining a 68-72% and 74-78% emergence at the time of typical wheat and sunflower sowing, respectively. Hence, depending on the timing of the first rain event, weed management options would vary. For example, if the first rains occurred early in the season, delaying sowing of wheat would be an effective strategy for managing *C. diluta* (Figure 6B).

Even if the first rain event is delayed, *C. diluta* emergence at wheat or sunflower planting was greater than expected. So the presence of a large *C. diluta* seed bank in these crops could explain why this weed is present at high densities and causes substantial crop yield reductions. As mentioned, almost 50% of the seeds sown did not apparently germinate and hence emerge in the two seasons of our study. It is possible that the viability of *C. diluta* seeds in the soil may be longer (> two years) than expected, at least for a certain proportion of the seed population, which could also explain the persistence of this species in arable crops of southern Spain. However, because of differences in the timing of soil disturbance in our experiment relative to that in commercial fields, the emergence patterns we observed and modelled for this weed may vary to some degree from those observed in commercial fields. That is, tillage occurring prior to the planting of both crops may have stimulated additional *C. diluta* emergence. Nosratti et al. (2017) and Joley et al. (2003) reported the stimulatory

influence of light on the germination of the congeners, *C. iberica* and *C. solstitialis*. Thus, further research is needed to more fully understand the emergence behavior of *C. diluta* and to modify the models developed in our study to better reflect actual practices carried out by growers in Spain.

The emergence of *Centaurea diluta* was effectively described in a large experiment that included data from 13 locations across Spain for one or two consecutive growing seasons. Moreover, the models developed showed good accuracies predicting the emergence of *C. diluta* from the natural seedbank. Our findings are potentially applicable to actual field situations by providing guidance on the optimal timing to implement weed control tactics or for crop sowing. However, additional experiments must be performed to integrate the possible effect of timing of soil disturbance prior to crop sowing on the emergence pattern of *C. diluta*.

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**Table 1.** Location, sowing date, and soil texture for the 11 experimental field sites in Spain.

Location	Abbreviation	Latitude	Longitude	Sowing dates	sand (%)	silt (%)	clay (%)
1 Barcelona ‡	BAR	41°16'33''N	01°59'14''E	10/14/2016	37.61	36.65	25.75
2 Córdoba ‡	COR	37°51'32''N	04°48'03''W	10/17/2016	35.1	35.27	29.63
3 Lleida ‡	LLE	41°37'41''N	0°35'32''E	10/11/2016	31.25	38.01	30.74
4 Madrid ‡	MAD	40°27'29''N	03°45'01''W	10/10/2016	74.72	7.44	17.84
5 Sevilla 2H ‡	2H	37°21'01''N	05°53'35''W	10/11/2016	36.02	31.3	32.67
6 Sevilla ETSIA ‡	ETSIA	37°21'07''N	05°56'20''W	10/11/2016	38.83	28.76	32.4
7 Sevilla FTS	FTS	37°07'39''N	05°40'37''W	10/21/2016	15.41	42.34	42.25
8 Sevilla Garden †	GAR	37°21'07''N	05°56'20''W	10/11/2016	-	-	-
9 Toledo	TOL	40°03'18''N	04°25'33''W	10/11/2016	49.72	21.11	29.17
10 Valladolid	VLL	41°38'49''N	04°38'49''W	10/18/2016	27.39	31.53	41.07
11 Zaragoza ‡	ZAR	41°43'46''N	0°48'28''W	10/07/2016	27.94	40.91	31.14

† Sevilla Garden experiment was conducted using 35-L pots containing a mixture of 50%

sand and 50% peat moss.

‡ In these locations, the experiments were conducted during an additional season (2017-18).

**Table 2.** Average percentage emergence ( $\pm$  SE) of *Centaurea diluta* across eleven experimental locations in Spain during two growing seasons.

Location	Emerged (%)		Non emerged (%)
	2016-17	2017-18	
BAR	17.8 (3.5) bcd	11.0 (5.9) ab	71.3
COR	40.8 (4.7) ab	21.3 (3.7) a	38
LLE	41.3 (6.9) ab	19.0 (5) ab	39.8
MAD	52.3 (1.9) a	2.8 (0.8) b	45
2H	49.5 (6.7) a	6.5 (2.9) ab	44
ETSIA	33.0 (8.1) abc	7 (4.1) ab	60
FTS	16.3 (4.5) cd	-	-
GAR	53.5 (8.3) a	-	-
TOL	8.8 (1.6) d	-	-
VLL	63.0 (11.4) a	-	-
ZAR	51.3 (5.6) a	9.5 (3.1) ab	39.3
Total	38.9 (1.6)	11.0 (1.0)	48.2 (1.8)

Values within a column followed by the same letter are not significantly different according to Tukey's test ( $\alpha = 0.05$ ). Data for 2016-2017 were transformed ( $x^{0.1}$ ) to meet requirements for ANOVA, but non-transformed means are shown.

**Table 3.** RMSEP values obtained from the thermal time and hydrothermal time models for each experimental location where the total seedling emergence was higher than 10 %.

Location	RMSEP Thermal time	RMSEP Hydrothermal time
BAR	5.0	5.5
COR	15.7	11.6
LLE	8.0	9.9
MAD	4.8	5.9
2H	17.9	12.3
ETSIA	14.8	14.7
FTS	7.8	9.6
GAR †	9.6	-
VLL	23.9	26.8
ZAR	7.6	7.2
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BAR (17-18)	6.7	7.6
COR (17-18)	7.3	6.1
LLE (17-18)	5.8	5.7
Average	10.8	10.7

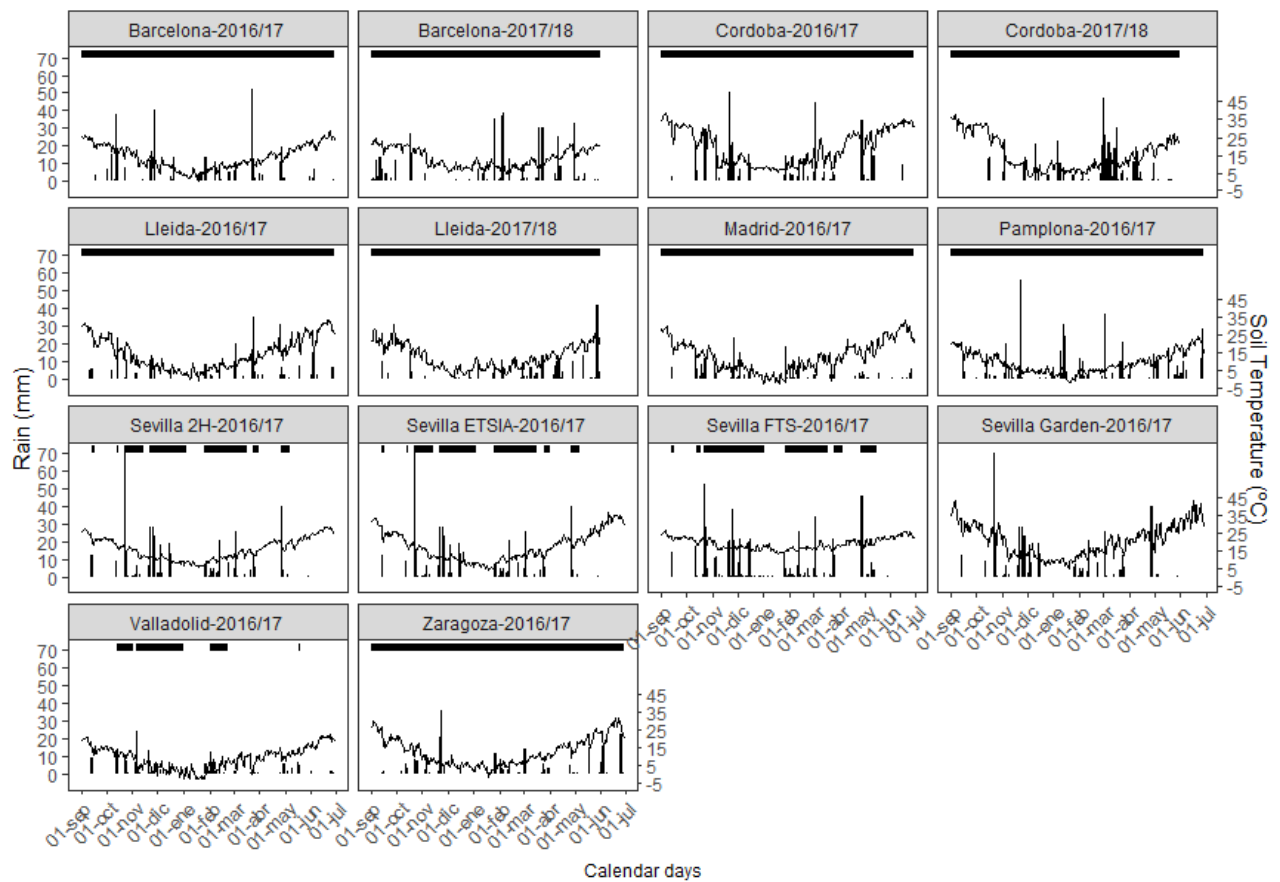
† For the Sevilla Garden site, only the thermal time model was tested because water potential could not be estimated using the equations described in Saxton and Rawls (2006).



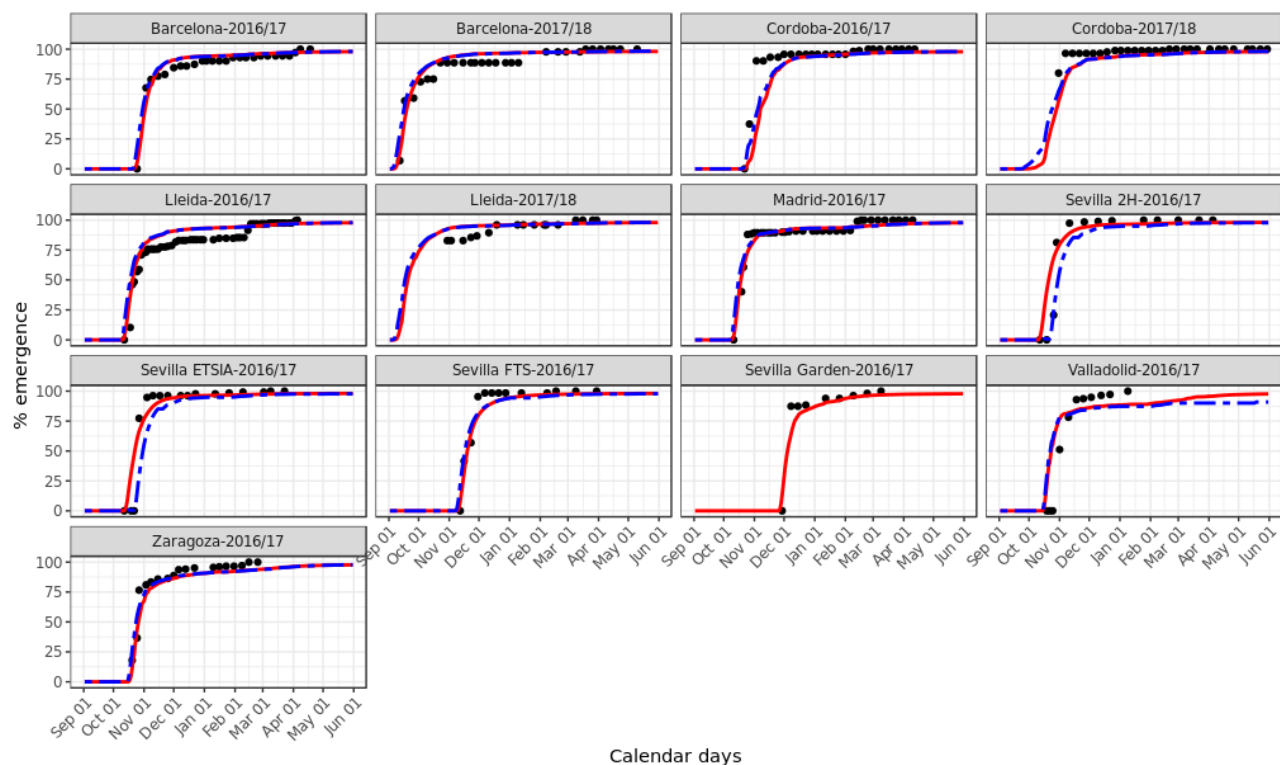
## Figure Legends



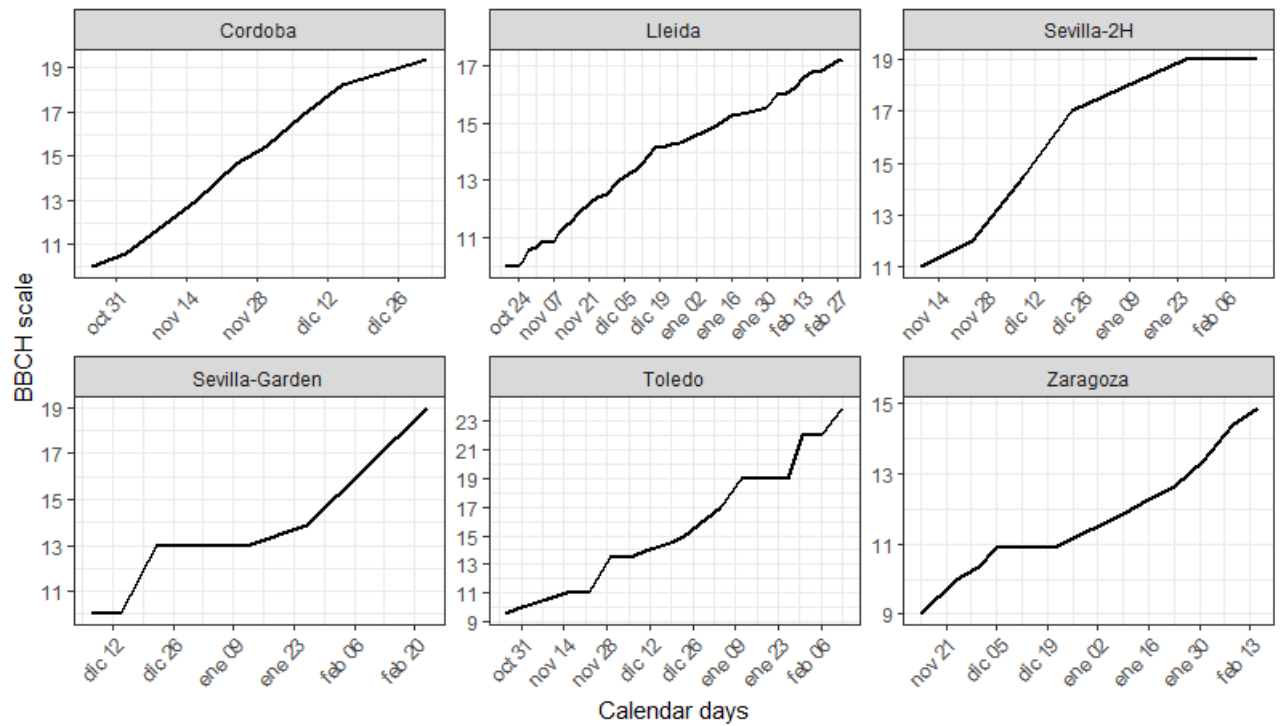
**Figure 1.** Locations in blue indicate areas in Spain where *Centaurea diluta* is considered a troublesome weed whereas locations in red indicate areas where this weed is present but currently not considered problematic.



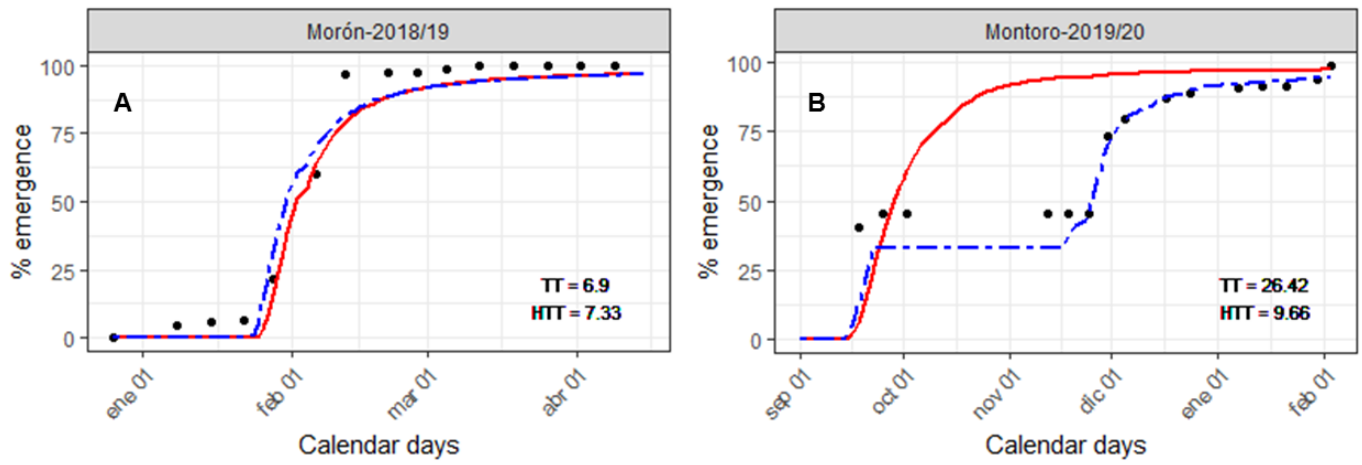
**Figure 2.** Precipitation (bar) and daily mean soil temperature (line) at the locations where more than 10 *Centaurea diluta* seedlings were recorded. The black bar at the top of each graph represents the period for adequate hydrothermal degree accumulation according to the model.



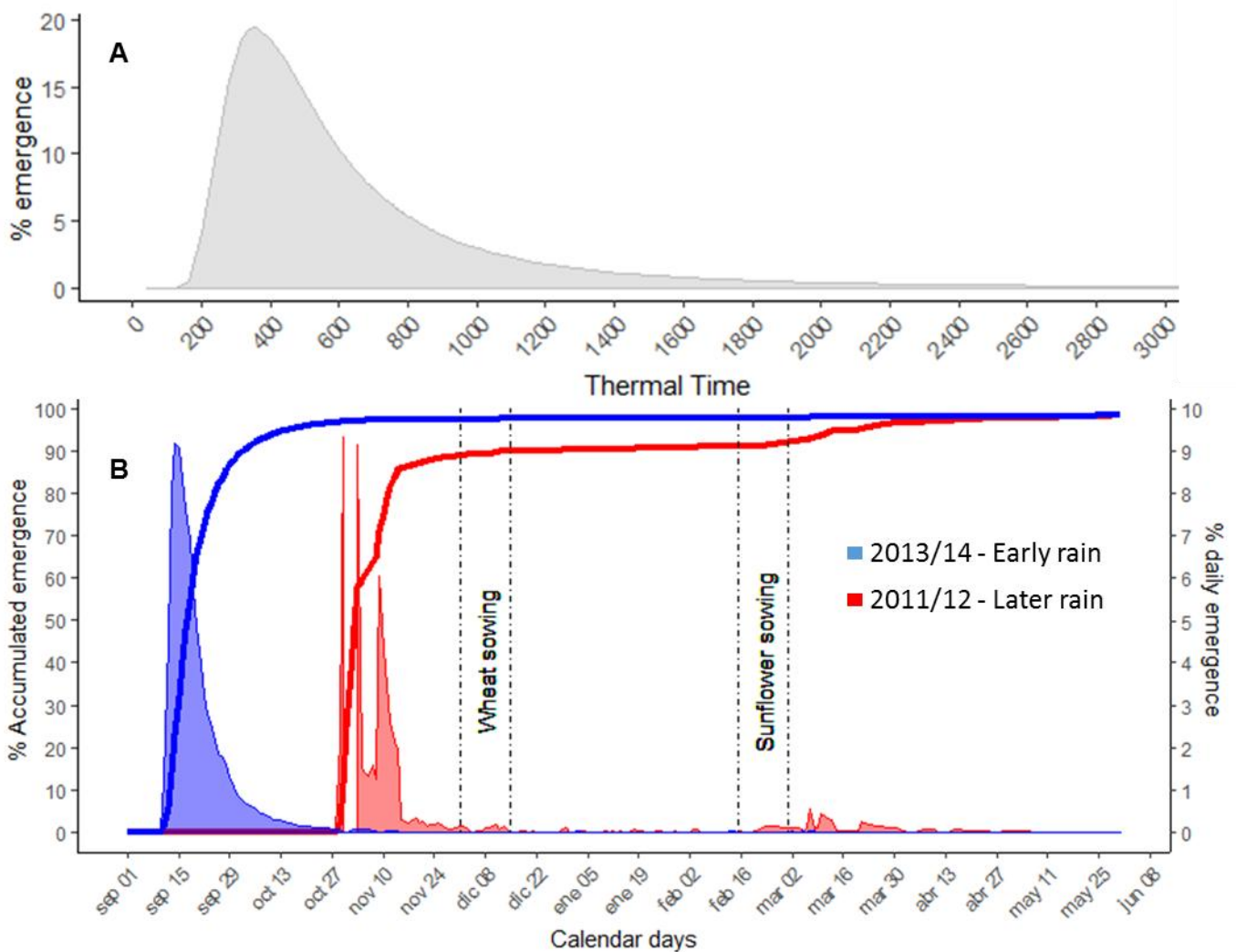
**Figure 3.** Predicted emergence of *Centaurea diluta* using the three parameters Weibull model based on thermal time (red solid line) and hydrothermal time (dotted blue line) for all locations where more than 10 *Centaurea diluta* seedlings were recorded. Observed seedling emergence is shown by the black dots.



**Figure 4.** Early phenological stage of *Centaurea diluta* using the BBCH scale, for three northern sites (Toledo, Zaragoza and Lleida) and for three southern sites (Sevilla-Garden, Sevilla-2H and Córdoba) in Spain in 2016-17.



**Figure 5.** Predicted emergence of *Centaurea diluta* using the three parameters Weibull model based on thermal time (red solid line) and hydrothermal time (dotted blue line) for the independent experiments used for model validation. Observed seedling emergence is shown by the black dots.



**Figure 6.** A) Density function (Weibull equation derivative) of *Centaurea diluta* emergence relative to thermal time; B) Cumulative percentage emergence (line) and daily percentage emergence (area) of *Centaurea diluta* predicted by the model using weather data from 2011-12 (later rain event, red) and 2013-14 (early rain event, blue).