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Original research article

Emergence of field pennycress (*Thlaspi arvense* L.): comparison of two accessions and modelling

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Running title: Emergence of *Thlaspi arvense* L.

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1 Abstract:

2 • *Background and aims*: Many weed species are becoming rare due to intense
3 agricultural management, which leads to a decrease of biodiversity in agroecosystems.
4 Cultivating some of these species for their oilseed content may help preserve them while
5 profiting agronomically. *Thlaspi arvense* is one of these species with potential as a crop.
6 Knowledge of emergence patterns using modeling can help to make decisions for its
7 management, whether for conservation or production purposes.

8 • *Methods*: The emergence of two accessions of *T. arvense*, one from Spain and the
9 other from USA, sown in Spain (Almenar) and USA (Morris), over two seasons (2011-12
10 and 2012-13) and in Riga (Latvia) over one season (2012), was followed to compare
11 patterns and extent, as well as to develop emergence prediction models based on
12 hydrothermal time (HTT) and photohydrothermal time (PhHTT).

13 • *Key results*: Emergence of the USA accession was significantly higher than that of the
14 Spanish accession. Both accessions presented two emergence peaks (autumn-winter and
15 spring) in both localities, but while these peaks could be considered as two different
16 flushes in Spain, they appeared to be a single flush disrupted by low winter temperatures
17 in USA. On the other hand, HTT based model was applicable for both accessions with
18 less precision, while PhHTT based one seemed more accurate in most cases but failed in
19 certain circumstances for the USA accession.

20 • *Conclusions*: Precipitation is the determining factor affecting the establishment of *T.*
21 *arvense* populations. The differences in emergence patterns among accessions suggest
22 that some accessions might be more amenable to being used as crop. The two models
23 developed in this work predicted quite accurately the emergence of *T. arvense* for both
24 accessions. Finally, the inclusion of photoperiod in the hydrothermal time equation,

1 creating a new unit that we have called photohydrothermal time, offers a possibility to
2 obtain more accurate models.

3

4 **Keywords:** *Brassicaceae*, hydrothermal time, oilseed species, photohydrothermal time, rare
5 weed

6

1 INTRODUCTION

2 *Thlaspi arvense* L. is a worldwide weed of great interest due to its high oilseed content
3 (Zanetti *et al.*, 2013) and potential use as a feedstock for biofuel (Moser *et al.*, 2009).
4 Although many studies have been conducted to analyse its oil quality (Davis *et al.*, 1999; Carr,
5 1993; Kumar & Tsunoda, 1980; Schroeder *et al.*, 1974), little is known about its proper
6 agronomic management (Zanetti *et al.*, 2013). Due to its winter annual cycle and relatively
7 early harvest date, it could be combined with a summer crop for double-cropping (Fan *et al.*
8 2013). Its growth characteristics make it suitable as a winter crop in Mediterranean climates
9 (Zanetti *et al.*, 2013), where it could be alternated with irrigated crops, as proposed for other
10 crop species by Meza *et al.* (2008). As a winter annual, it can also double as a cover-crop to
11 sequester excess soil nitrogen, reduce erosion, provide spring cover, and suppress other weeds
12 (Dorn *et al.*, 2013).

13 Conversely, in many areas where *T. arvense* is not used as a crop, it is a weed that is
14 becoming rare. In Northeastern Spain, for example, high agricultural inputs and the
15 establishment of conservation tillage systems have reduced its populations to such low levels
16 that it has disappeared in many areas (Cirujeda *et al.*, 2011). For this reason, the introduction
17 of *T. arvense* as a crop could guarantee the conservation of this species in fields, which may
18 lead to other benefits, such as an increased crop diversity in agroecosystems, and increased
19 pollen sources for pollinators including domestic and wild bees (Decourtey *et al.*, 2010;
20 Brodscheneider & Crailsheim, 2010).

21 In this sense, knowledge about the emergence pattern of *T. arvense* in the field is
22 important to manage its populations, whether for conservation or production purposes.
23 Emergence is the most important step in the establishment of a plant, as its timing determines
24 the success of the seedling (Forcella *et al.*, 2000). Emergence models have been successfully
25 developed for predicting weed emergence in Mediterranean-type climates and non-irrigated

1 fields. Moreover, hydrothermal time models (or soil moisture based corrected thermal time
2 models) have been developed to predict the emergence of several weeds such as *Galium spp.*
3 (Royo-Esnal *et al.*, 2010), *Bromus diandrus* (García *et al.*, 2013) and *Lolium rigidum*
4 (Izquierdo *et al.*, 2013). Although these models have been developed to predict emergence to
5 control these weeds, they might also be used to better decide when to sow them as a crop.

6 Emergence can vary between populations of *T. arvense*. For instance, Hazebroek &
7 Metzger (1990b) found two *T. arvense* accessions, differing in requirement of cold
8 temperature for germination. But when these two seed types were grown together, no
9 significant differences were found in the phenology of reproductive development (Hazebroek
10 & Metzger, 1990b). Saarinen *et al.* (2011) found germination differences between seeds
11 produced by autumn emerging and spring emerging individuals within the same population.
12 Maternal genetic differences also affect the competitiveness of *T. arvense* plants (Susko &
13 Cavers, 2008).

14 The objective of this work was to compare the emergence of two wild populations of
15 *T. arvense* coming from contrasting climates, one from a Mediterranean climate (Teruel,
16 Spain) and the other from a continental temperate climate (Morris, Minnesota). Emergence
17 models were developed based on 1) hydrothermal time, and 2) hydrothermal time corrected
18 with photoperiod, to best characterize emergence under both climatic conditions.

19 20 MATERIAL AND METHODS

21 *General set up and site descriptions*

22 Seeds of *Thlaspi arvense* were harvested at maturity between June and July 2011 and 2012 in
23 Camarillas (40°38'39''N-0°48'35''W, Teruel, Spain) and Morris (45°43'36''N-95°49'17''W,
24 Minnesota, USA). Seeds were stored dried at laboratory conditions until sown for field

1 studies. Seeds of the Spanish population were sent to Morris and seeds of the USA population
2 to Lleida, so that both populations were sown in both locations each season. Field trials were
3 conducted from autumn to spring in two consecutive seasons (2011-12 and 2012-13) in a
4 commercial cereal field (without crop in the plots) in Almenar (41°46'36''N-0°32'7''E,
5 Spain) and in an experimental field in Morris (as above). A set of seeds was also sent to Riga
6 (Latvia), where the two different populations were sown in spring 2012 in the Botanical
7 Garden of the University of Latvia (56°57'02''N-24°06'57''E) in the same way as in Almenar
8 and Morris.

9 Seeds were sown at 1 cm depth in 1 m² plots at a rate of 1000 seeds per plot, with four
10 replications. Sowing was performed in four rows per plot, each with 250 seeds, to facilitate
11 hand weeding of the plots and to simulate cultivation conditions. Emergence of seedlings was
12 followed weekly until May and newly emerged seedlings were identified with colored wires.
13 In Morris, seeds were sown on 19 and 18 September respectively in 2011 and 2012, while due
14 to climatic conditions, they were sown on 2 November in 2011 and on 4 October in 2012 in
15 Almenar. In Riga seeds were sown on 1 May 2012. Plots were not watered, so that emergence
16 of *T. arvense* was conditioned mainly by climatic conditions.

17 After the first season, seed shed was avoided by severing the surviving plants at the
18 soil surface, and the emergence of seedlings in plots sown in autumn 2011 was followed also
19 until autumn 2012.

20 *Statistical analysis*

21 Differences in total percentage emergence between populations (Spanish vs USA), localities
22 (Almenar vs Morris vs Riga) and between seasons (2011-12 vs 2012-13) were performed with
23 three-way ANOVA. If interactions were found between factors, two-way ANOVA was
24 performed to separate the respective factors. If new interactions were found, a new separation

of factors was done. To satisfy normality and homogeneity of variance, emergence percentages were transformed by the function $\arcsin(\sqrt{x/100})$ if needed.

Weather data

Daily rainfall and maximum and minimum air temperatures were obtained from a meteorological station situated 4 km away in Almenar, while in Morris they were obtained from a standard meteorological station located at the experimental field. The weather data set from Riga came from a meteorological station at the University of Latvia (Latvian Environment, Geology and Meteorology Centre).

Model development

The model was developed with data from autumn and spring emergence periods of the Spanish population in Almenar in seasons 2011-12 and 2012-13. Simulated soil temperatures (thermal time, TT) and water potentials (hydrotime, HT) were used to calculate hydrothermal time (HTT) based on the equation described by Roman *et al.* (2000):

$$HTT = \sum (HT \times TT)$$

where $HT = 1$ when $\psi > \psi_b$, otherwise $HT = 0$; and $TT = T - T_b$ when $T > T_b$, otherwise $TT = 0$. ψ is the daily average water potential in the soil layer from 5 to 10 cm; ψ_b is the base water potential for seedling emergence; T is the daily average soil temperature in the soil layer from 5 to 10 cm and T_b is the base temperature for seedling emergence (Martinson *et al.*, 2007; Royo-Esnaola *et al.*, 2010). The soil depth chosen for the HTT estimation was 5 to 10 cm because it gave the best accuracy when fitting the HTT model. With this formula, growing degree days are accumulated only when the water potential and temperature conditions were higher than the base water potential and base temperature. The HTT was estimated using the

1 Soil Temperature and Moisture Model (STM²) (Spokas and Forcella, 2009). STM² requires as
2 input daily maximum and minimum air temperatures and daily precipitation, including
3 information on the geographical location and soil texture and organic matter. HTT were
4 accumulated over days beginning on the sowing date. The base water potential and base
5 temperature were determined iteratively calculating HTT using a set of water potentials (-5.0
6 MPa to -0.5 MPa at -0.1 MPa intervals) and temperatures (-5° to +2° C at 0.1°C intervals).
7 Namely, the scale of HTT was changed by modifying the ψ_b and the T_b until the highest
8 accuracy (R^2) was obtained for the relationship between HTT and cumulative emergence of *T.*
9 *arvense*. Based on a previous germination chamber experiment carried out in Lleida (data not
10 shown), a ceiling temperature (T_c) was estimated at nearly 25°C; for this reason, this
11 parameter was added for calculating the HTT. Estimation of this T_c was also made iteratively
12 (21° to 27° at 1°C intervals) together with ψ_b and T_b .

13 Due to emergence characteristics at the three sites, estimated HTT was corrected by
14 proportional daylight hours, considering daylight of 24h = 1, 12h = 0.5 and 0h = 0. The new
15 unit is hereafter called photohydrothermal time (PhHTT), which is the product of HTT and
16 day length. The process for developing PhHTT started with the parameters (T_b , ψ_b and T_c)
17 estimated for the HTT based model, and then modifying them if needed. Our reason to add
18 photoperiod was different than that given by Deen *et al.* (1998) to explain photothermal time.
19 For the emergence process, light is not needed, but daylight hours are warmer and the
20 emergence process therefore could be accelerated, while with colder night-hour temperatures,
21 metabolism slows down and so too does seedlings emergence.

22 The functional relationship between cumulative emergence and HTT and PhHTT was
23 described by a four parameter Weibull model:

24

$$y = a \left[1 - e^{-((x-x_0+b \ln 2^{1/c})/b)^c} \right]$$

where y is 0 if:

$$x < x_0 - b * \ln(2)^{(1/c)}$$

y is the percentage of emergence, x is time expressed as HTT, and a , b , c and x_0 are empirically derived constants: a , is the maximum percentage of emergence recorded, b is the rate of increase, c is a shape parameter and x_0 is the HTT required to obtain 50% of emergence. To make this Weibull model simpler, a was assumed to be 100% for each plot in each season. Fitting of the four parameter Weibull function for cumulative emergence was performed using SigmaPlot 11.0.

Validation of the emergence model

The developed model was validated with emergence data of different sites: first, the autumn and spring emergence data of the USA population of *T. arvense* sown in Almenar in 2011 and 2012; second, the emergence data of both Spanish and USA populations in Morris in 2011-12 and 2012-13; third, the data series of seedlings of both populations that emerged in Almenar in autumn 2012 of seeds sown in autumn 2011; and fourth, spring seedling emergence data from Riga in 2012. In every case, the adjustment of the model is shown with the estimated x_0 , as well as with the best x_0 for each data series. Agreement between predicted and actual emergence values was determined with the root-mean-square error predictor (RMSEP):

$$RMSEP = \sqrt{1/n \sum_{i=1}^n (x_i - y_i)^2}$$

where x_i represents actual cumulative percentage of emergence, y_i is predicted cumulative percentage of emergence, and n is the number of observations (Mayer and Butler, 1993). RMSE provides a measurement of the typical difference between predicted and actual values in units of percentage seedling emergence. The RMSEP ranges to evaluate the accuracy of the model are based on Royo-Esnal *et al.* (2010), which were: <5, excellent prediction; 5-10, very good prediction; 10-15, good prediction; >15, insufficient prediction. The lowest RMSEP values indicated that the emergence model fit had been optimized.

RESULTS

Climatic characteristics of Almenar, Morris, and Riga

The three sites differed in terms of temperature and precipitation. In Almenar, the 2011-12 season was quite warm, with a mean temperature (T_m) of 9.5°C in the period November-May and with only 9 days with mean temperatures below 0°C. Almenar was also dry (Figure 1A). Overall, rain amounted to 228 mm, compared to the historical mean for the same period (272 mm), with the following distribution: 101 mm in October-November 2011; 3 mm from December to 20 March 2012, and 122 mm from 20 March to 31 May. The 2012-13 season was cooler (T_m of 7.9 for the same period) and wetter (318 mm): 122 mm fell between October and November; 51 mm from December to end of March; and 145 mm from end of March to 31 May.

In Morris during 2011-12, T_m was 11.3 from 1 September to mid-November, after which it dropped below 0°C most days (T_m -4.9°C) until it rose again at the beginning of March,

1 having a Tm of 12.2°C from 9 March to 31 May (Figure 1B). In these periods, precipitation
2 (216 mm) was distributed as 41 mm in September-mid November, 9 mm from mid-November
3 to 9 March and 166 mm from 9 March to 31 May. In 2012-13, Tm was 10.2°C from 1
4 September to late November, -9.0°C from late November to early April, and 8.1°C from early
5 April to late 31 May. Only 56 mm of rain fell in 2012-13: 1 September to late November was
6 extremely dry, with only 40 mm (of which 9 fell on 10 November, the last day with Tm over
7 0°C); the drought continued over winter (8.5 mm) and persisted from early April to 31 May
8 (6.9 mm). Comparatively, Morris tended to be much drier than Almenar during the study
9 period (Figure 1A & 1B).

10 In Riga, the spring of 2012 was characterized by cool (14°C on average from 1 May to
11 30 June) and slightly humid weather (115 mm in the same period) (Figure 1C).

12 *Differences between populations and locations*

13 Table 1 shows total emergence obtained in each location, separating autumn and spring
14 emergence periods.

15 In general, the USA accession had significantly more emergence in almost every growing
16 season and locality, except in spring 2011-12 and spring 2012-13 in Almenar, and in autumn-
17 winter 2012-13 for seeds sown in 2011 (Table 1). When compared between locations,
18 emergence was more abundant in Morris for the USA accession, while for the Spanish
19 accession emergence was more abundant in Almenar, except in spring 2011-12. In relation to
20 the data from Riga, emergence percentages were much more similar to Almenar than Morris.

21 In Figure 2, besides reflecting the differences of the total emergences distributed throughout
22 the season, it can be observed that spring emergence started later in time in Almenar than in
23 Morris, probably due to the drought suffered in the first site from December to 20 March
24 (Figure 1A). It can also be observed that there was a delay of emergence in Morris during

autumn 2012 with respect to Almenar. In this case, the delay was also provoked by the drought suffered in USA in autumn 2012 (Figure 1B).

Emergence models development.

The emergence characteristics of *T. arvense*, with an autumn-winter peak and another spring peak, made possible the development of the model based on four series of data: Autumn-Winter 2011-12 and 2012-13 and Spring 2011-12 and 2012-13 (Figure 3). The start for the HTT accumulation was established at the time of sowing for the autumn-winter emergences, while it was established on 25 January for the spring emergences in both years and was near optimum between 15 January and 1 February. T_b was established at -2.5°C , although for the HTT based model, best R^2 (0.883) values were obtained between -2.5° and -4.7°C . T_c was established at 24°C and ψ_b at -2.6 MPa. Estimates of the variables b , c and x_0 fitted to HTT for *T. arvense* are 112.8 ± 19.1 , 1.01 ± 0.24 and 442 ± 7.9 (Figure 3A).

For the PhHTT based model, some factors had to be changed because b and c parameters were not significant with the HTT conditions. Factors changed included the soil depth range considered for HTT accumulation, which was changed to 4-7 cm (instead of 4-8 cm), ψ_b was established at -2.7 MPa, T_c was established at 25°C , and T_b was maintained at -2.5°C . This resulted in a better adjusted model ($R^2 = 0.973$) (Figure 3B) with the following parameters: 132.4 ± 45.6 for b , 4.49 ± 1.70 for c and 215.3 ± 1.7 for x_0 .

Based on the ranges estimated by Royo-Esnal *et al.* (2010), the RMSE values for the HTT-based model are not accurate enough with the estimated x_0 for the autumn-winter 2011-12 and spring 2012-13 series, while good estimates were obtained for spring 2011-12 and very good (almost excellent) for autumn-winter 2012-13 (Table 2). When RMSE was calculated for the PhHTT model, it improved in three of the four cases, changing the accuracy from not sufficient to very good for autumn-winter 2011-12 and spring 2012-13, and from good to very

good for spring 2011-12 (Table 2). The loss of accuracy in autumn-winter 2012-13 was not relevant, as it was still very good (from 5.4 to 6.4).

Validation of the model

The emergence predicted by the models was validated with the cumulative emergences observed in four different types of data series (Figures 4 A-H). The estimated RMSEP for each series and the best x_0 are shown in Table 3.

In the data series of the USA accession sown in Almenar in autumn 2011 and 2012, the accuracy of the prediction was good in autumn-winter and spring 2011-12, and in spring 2012-13 (RMSEP = 12.2 to 12.6 in every case, Table 3) and very good in autumn-winter 2012-13 (5.6). These results were not improved with the PhHTT model, with which autumn-winter 2011-12 and spring 2012-13 received insufficient predictions (RMSEP = 23.1 and 15.9, respectively) (Table 3). However, variation of x_0 (Table 3) improved the accuracy of the PhHTT model to give good predictions (RMSEP < 15).

The data series of Spanish and USA accessions grown in Morris in seasons 2011-12 and 2012-13 were special cases (Figure 4B). When trying to adjust the model to autumn-winter and spring emergence separately, the model did not adjust well. However, when the emergence was considered as continuous from sowing to June, the model adjusted considerably better for the Spanish accession (RMSEP = 14.8 in 2011-12 and RMSEP = 6.2 in 2012-13), but underestimated the emergence of the USA accession (RMSEP = 25.7 and 18.3, respectively for each season). For this reason, a new x_0 was estimated at 375 HTT (grey line in the figure), which gave good predictions for both accessions (13.6/14.6 and 12.9/6.4 in 2011-12/2012-13, respectively, for the Spanish and USA accessions). The PhHTT model improved the emergence predictions, except for the Spanish accession in 2012-13. Contrary to what happened in Almenar, best x_0 was different for each season, being $x_0 = 149$ in 2011-12

1 and $x_0 = 240$ in 2012-13, resulting good predictions in all cases (RMSEP between 14.1 and
2 14.7) (Figure 4D).

3 When analysing the emergence and applying the model to the Spanish and USA
4 accessions sown in 2011 that emerged in autumn-winter 2012-13 (Figure 4C), the first
5 challenge was to establish a time zero (i.e., starting point) for emergence. These seeds
6 remained buried in soil for one year and, thus, a starting point for HTT accumulation had to
7 be established earlier than the sowing date in 2012-13, which had been 29 September,
8 according to first important rain event in autumn (40 mm in two days after 19 days without
9 rain). The prediction of the Spanish accession was very good (RMSEP = 7.8), but in this case
10 it overestimated the emergence of the USA accession (RMSEP = 16.2) (Figure 4C).
11 Calibration of x_0 to 460 HTT maintained a very good prediction for the Spanish accession
12 (8.7) and improved that of the USA accession (14.2). The model based on PhHTT improved
13 the prediction of the USA accession without changing the estimated x_0 , as well as maintained
14 a good prediction for the Spanish accession (Figure 4F and Table 3).

15 Finally, the model predicted very well the emergence of the USA accession in Riga
16 (RMSEP = 9.8), but failed when predicting the Spanish accession (RMSEP = 18.8) (Figure
17 4D). This failure was overcome by adjusting the x_0 to 352 (grey line in the figure), which not
18 only improved the simulation of the Spanish accession (RMSEP = 12.8), but also that from
19 USA (RMSEP = 4.4). The PhHTT-based model improved in both cases the initial HTT-based
20 prediction (RMSEP = 7.7 and 16.2 for the USA and Spanish accession respectively), and the
21 prediction was considerably improved after calibrating x_0 to 275 PhHTT (Figure 4H).

22

23 DISCUSSION

1 The emergence of *Thlaspi arvense* is conditioned by moisture in the soil (Baskin & Baskin,
2 1989). Temperature is essential, but its variation from one season to the next would only
3 advance or delay its emergence. In contrast, lack of precipitation can prevent seedlings from
4 emerging, as happened in winter 2011-12 in Almenar and autumn 2012 in Morris, which led
5 to very little emergence compared to the seasons when moisture was not lacking in either
6 location. Similar results were obtained by Hazebroek & Metzger (1990a), who state that the
7 major limiting resource for non-dormant seeds on the soil surface is water availability.

8 Another concern is the great differences in percentage of emergence observed between
9 both Spanish and USA accessions. In nine conditions out of ten (combination of sites and
10 seasons, Table 1), USA accession percentages of emergence were higher than for the Spanish
11 accession. This could be due to different dormancy levels of the seeds or different
12 requirements for emergence (and germination) that might be caused by the climatic conditions
13 where the seeds were produced. A recent study by Saarinen *et al.* (2011) near Helsinki
14 showed that seeds produced by plants that overwintered under field conditions – more similar
15 to Minnesota conditions - germinated significantly more than those produced by plants
16 subjected to a warming treatment (5°/10°C night/day) in January – more similar to Teruel.
17 These results are confirmed by the difficulties found in developing a common model to
18 predict the emergence of both accessions. A less accurate model (HTT-based model)
19 predicted the emergence of both accessions quite well, although some important differences
20 were found between them mainly in the emergence rate in Morris and Riga, where an
21 insufficient prediction was always obtained for one of the accessions. The development of a
22 more accurate model, which took into account day length, improved the prediction in most
23 situations but it did not in the USA accession grown in Almenar in autumn-winter 2011-12
24 and spring 2012-13, which indicates that some conceptual aspects of emergence modeling
25 still must be improved.

1 The developed models predict *T. arvense* emergence relatively well, but the
2 importance of the inclusion of the day length must be underlined. Morris and Riga present
3 short emergence periods before autumn and after the spring equinox, respectively, when
4 daylight hours are greater than in Almenar. This factor corrects, in part, the differences
5 between the three sites and improves the accuracy of the prediction. Despite this, as it has
6 been said before, differences of dormancy levels between accessions may also lead to a lack
7 of accuracy in some cases.

8 The inclusion of day length to create the new photohydrothermal time (PhHTT)
9 concept is based on the photothermal time concept, with which phenological growth of
10 *Ambrosia artemisiifolia* (Deen *et al.*, 1998), *Raphanus raphanistrum* (Cousens *et al.*, 2001)
11 and *Avena fatua* (Dai *et al.*, 2012) were studied. As previously explained in the material and
12 method section, the emergence process does not require light (it could happen during the
13 night). However, besides the reason given before for using day length (speed of metabolism),
14 whether this new unit (PhHTT) could help characterize germination requirements that affect
15 emergence of *T. arvense* in the field needs further study.

16 *Implications for a Thlaspi arvense crop*

17 Although the emergence of *T. arvense* showed two peaks of emergences in both
18 Almenar and Morris, an important difference occurred between the two sites. While
19 emergence in Almenar could be described as two independent peaks that could be described
20 with the models, the emergence in Morris (and probably in Riga, but this was not proven in
21 this experiment) follow a one peak pattern split into two parts. Thus, the model described the
22 emergence from autumn to spring as a unique series of emergence. This result is explained by
23 both dormancy characteristics and HTT (or PhHTT) cumulated before winter temperatures
24 drop under -2.5°C in Morris. In general, dormancy of *T. arvense* is broken during summer
25 (Baskin & Baskin, 1989) and emergence begins in autumn. In Almenar, those seeds that do

1 not emerge in autumn may have a morphological dormancy due to under-developed embryo.
2 Seeds are able to after ripen during winter and emerge in spring (Baskin & Baskin, 1989). In
3 the case of Morris, when *T. arvense* was sown in September low temperatures came before
4 seeds cumulated enough HTT (or PhHTT) for emergence. After winter, seeds behaved as if
5 they continued cumulating HTT, and most of them emerged at the end of March and in April.

6 These differences in the emergence behaviour show that cropping of *T. arvense* must
7 be focused differently. In northeastern Spain or in a Mediterranean climate situation it would
8 be better to sow the crop in autumn, so that most seedlings could emerge (if there is enough
9 rain). These seedlings would have enough time to grow, flower, and produce seeds by the end
10 of spring, while those seedlings that emerge in spring would lag in growth and development
11 as compared to those that emerged in autumn. Moreover, for plants that emerge in the spring,
12 the lack of moisture due to high temperatures during the summer could kill many individuals
13 or prevent them from producing high yields, unless they are watered.

14 On the other hand, climatic characteristics like those found in Morris must be studied
15 in more detail for *T. arvense*. Most seedlings emerge in spring, but do those sown in autumn
16 emerge quicker than those sown in spring? Here we can only compare the Morris and Riga
17 situations: in both cases *T. arvense* needed less HTT for 50% emergence than in Almenar,
18 with little difference between both sites (350-375 HTT), but when PhHTT was applied,
19 accessions sown in Morris needed 175 and 240 PhHTT, while they needed 275 PhHTT in
20 Riga. Accessions in Morris emerged earlier in time and with fewer PhHTT, which could give
21 them an advantage when growing in spring.

22 *Future challenges*

23 The development of these two models is an important step forward in understanding
24 this valuable species. The models could be used to predict the emergence of *T. arvense*. The

1 HTT-based model could be used in north-eastern Spain with different accessions, while the
2 PhHTT-based model seems more reliable for predicting the emergence of the Spanish
3 accession in different sites.

4 Despite this, poor seed germination, and hence, emergence is a major issue that must
5 be improved before *T. arvense* can be produced as a reliable crop. In the present study, this
6 was evidenced by the significant variation in seedling emergence from one season to the next.
7 Moreover, in the case of the Spanish accession, emergence was very poor (maximum of
8 19.4% of seed sown in a whole season), which would require sowing a high quantity of seeds
9 to obtain sufficient stand establishment to produce a harvestable crop. In this sense, selection
10 of seeds by size might improve germination percentages, as this is positively correlated with
11 seed mass (Susko & Cavers, 2008). Moreover, larger seeds also tend to produce more
12 competitive individuals and higher yields (Susko & Cavers, 2008). Additionally, storage of *T.*
13 *arvense* seeds for over a year at room temperature could also be considered, as it has been
14 demonstrated to increase germination percentages up to 85% (Isbell *et al.*, 2011). Similar to
15 our study, where accessions had slightly different emergence characteristics, Isbell (2009) has
16 also shown this to occur in other known accessions. Whether those differences are due to
17 parental effect, or are intrinsic for each accession must be studied. This would also allow an
18 opportunity to seek the best accession for cropping in each location, depending on their
19 agronomic traits.

20 Furthermore, the possibility of alternating this potential crop with another summer
21 crop (e.g., maize or soybean) is feasible, but mainly in climates with mild winters. In climates
22 with long cold winters such as Minnesota, USA, its emergence is stopped in the winter and
23 resumes in the spring, and in this instance, plants might not mature soon enough before the
24 next crop sowing (Fan *et al.*, 2013).

CONCLUSIONS

To establish sufficient plant populations to crop *Thlaspi arvense*, the most limiting environmental factor is precipitation. This species presents autumn-winter and spring emergence peaks, which can be interpreted as two independent flushes in Spain and as one single flush divided into two by low winter temperatures in Minnesota. In both sites, long droughts decreased emergence, while sufficient precipitation allowed it to increase.

The differences in emergence patterns among accessions suggest that some accessions might be more amenable to being used as crop, although improvement of seed germination and emergence may be required for certain accessions such as the Spanish one. However, this variability may also offer opportunities to decide the best cropping management for this species.

The two models developed in this work predicted quite accurately the emergence of *T. arvense* for both accessions. The HTT based model seems to be less accurate than the PhHTT based model, although further research is needed to determine if they could be applied to other accessions different than those used in the present study. Finally, the inclusion of photoperiod in the hydrothermal time equation, creating a new unit that we have called photohydrothermal time, offers a possibility to obtain more accurate models.

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Table 1: Total percentages of autumn and spring emergence (% of seed sown $\pm$ SE) in 2011-12 and 2012-13 for the Spanish and USA accessions of *T. arvense*, and total emergence of both accessions in Riga in spring 2012. Aut-Wint columns refer to total emergence that occurred during autumn or autumn and winter. Different letters represent significant differences; lower case letters: differences between accessions for each locality in the same season (Aut-Wint or Spring); capital letters: differences between growing seasons within an accession and locality.

		2011-12		2012-13		†2012-13 old	
		Aut-Wint*	Spring*	Aut-Wint	Spring*	Aut-Wint	Spring
Almenar	Spanish <i>T. arvense</i>	0.7 $\pm$ 0.1 bC	4.3 $\pm$ 0.7 aA	6.4 $\pm$ 0.9 bA	1.9 $\pm$ 0.6 bB	1.6 $\pm$ 0.4 aB	0
	USA <i>T. arvense</i>	2.1 $\pm$ 0.4 aB	2.2 $\pm$ 0.6 aA	22.7 $\pm$ 2.0 aA	3.3 $\pm$ 0.9 bA	2.1 $\pm$ 0.3 aB	0
Morris	Spanish <i>T. arvense</i>	0.2 $\pm$ 0.1 bA	19.2 $\pm$ 2.6 bA	0.03 $\pm$ 0.0 cA	4.3 $\pm$ 1.2 bB		
	USA <i>T. arvense</i>	17.9 $\pm$ 3.2 aB	50.9 $\pm$ 2.8 aA	5.3 $\pm$ 1.3 bC	50.6 $\pm$ 2.7 aA		
Riga	Spanish <i>T. arvense</i>		0.8 $\pm$ 0.7 b				
	USA <i>T. arvense</i>		6.4 $\pm$ 2.1 a				

*two way ANOVA gave significant interaction between factors. Thus, factor accession was analysed for each location separately.

† 2012-13 old refers to seedling emergence that occurred in season 2012-13 from seed that was sown in autumn of 2011-12.

1 Table 2: RMSE for the four series of data with which the HTT and PhHTT models were developed.

	RMSE (HTT)	RMSE (PhHTT)
Autumn-Winter 2011-12	16.7	8.7
Spring 2011-12	14.5	3.5
Autumn-Winter 2012-13	5.4	6.4
Spring 2012-13	16.7	9.9

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1 Table 3: RMSEP for the four series of data with which the HTT and PhHTT models were validated, as well as
2 the best x_0 estimated for each series of data.

		RMSEP		Best x_0	
		HTT ($x_0 = 442$)	PhHTT ($x_0 = 215$)	HTT	PhHTT
USA accession in Almenar	Aut-Wint 2011-12	12.4	23.1		
	Spring 2011-12	12.6	11.6		
	Aut-Wint 2012-13	5.6	5.2	442	175
	Spring 2012-13	12.2	15.9		
Accessions in Morris	Spanish 2011-12	14.8	6.9		
	USA 2011-12	25.7	22.2	375	149
	Spanish 2012-13	6.2	17.4		
	USA 2012-13	18.3	11.4	398	240
Seeds sown in 2011 emerged in Aut-Wint 2012	Spanish	8.1	12.1		
	USA	16.2	12.0	460	215
Accessions in Riga	Spanish	18.8	16.2		
	USA	9.8	7.7	352	275

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- 1 Figure 1: Climatic conditions of Almenar (A) and Morris (B) in the seasons 2011-12 and 2012-13, and in Riga
- 2 (C) in spring 2012. Lines are mean daily temperatures and columns are total daily precipitation.
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3 Figure 2: Distribution of the percentages of emergence of Table 1 throughout the two growing seasons, 2011-12
 4 and 2012-13, in Almenar (A) and in Morris (B). Black line: Spanish accession; grey line: USA accession.

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3 Figure 3: Emergence models developed with cumulative emergence data from Spanish accession grown in
 4 Almenar in the seasons 2011-12 and 2012-13 for the hydrothermal time based model (HTT) (A); and the
 5 photohydrothermal time based model (PhHTT) (B). Line: predicted emergence; black dots: autumn-winter
 6 emergence 2011-12; white dots: spring emergence 2011-12; black triangles: autumn-winter emergence 2012-13;
 7 white triangles: spring emergence 2012-13.

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Figure 4: Predicted (black line) and observed (symbols) cumulative emergence for the different data series used to validate the models. The grey lines represent the adjusted model after varying x_0 specifically for the different

1 data series. HTT-based models are shown in A, C, E, and G, and PhHTT models in B, D, F, and H. Figures 4A-
2 B: USA accession sown in Almenar in Autumn 2011 and 2012; black dots, autumn-winter emergence 2011-12;
3 white dots, spring emergence 2011-12; black triangles, autumn-winter emergence 2012-13; white triangles,
4 spring emergence 2012-13; grey line, adjusted model with $x_0 = 175$ PhHTT (B). Figures 4C-D: Spanish (white
5 dots and triangles) and USA (black dots and triangles) accessions sown in September 2011 (dots) and 2012
6 (triangles) in Morris (MN, USA); straight grey lines, adjusted models with $x_0 = 375$ HTT (C) and $x_0 = 149$
7 PhHTT (D); intermittent grey line, $x_0 = 240$ PhHTT (D). Figures 4E-F: Spanish (white dots) and USA (black
8 dots) accessions sown in Almenar in November 2011 and emerged in Autumn-Winter 2012-13; grey line,
9 adjusted model with $x_0 = 460$ HTT (E). Figures 4G-H: Spanish (white dots) and USA (black dots) accessions
10 sown in Riga in spring 2012; grey lines, adjusted models with $x_0 = 352$ HTT (G) and $x_0 = 275$ PhHTT (H).

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