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Describing *Polygonum aviculare* emergence in different tillage systems

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Running head: Modeling *Polygonum aviculare* emergence

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Summary

Effects of four tillage systems (direct drill, subsoiler, chisel plough and mouldboard plough) on the dynamics of *Polygonum aviculare* populations were studied over three growing seasons. Cumulative emergence on a weekly basis was determined. Cumulative emergence from two years of chisel plough was used to develop an emergence model for *P. aviculare* based on hydrothermal time. Results showed that direct drilling, which had the highest seed yields of winter cereal crops every season, was the unique soil management system that lowered *P. aviculare* populations because of effective weed emergence reduction. The model accurately described seedling emergence in different tillage systems, although it failed in direct drilling, probably due to very low numbers of emerged seedlings. To better control this weed, direct drilling may be the best tillage option, but if this can not be implemented, the hydrothermal time model is a practical tool that can describe the relative proportions of emergence and assist in the timing for management operations of *P. aviculare* in different tillage systems.

Keywords: chisel, direct drilling, emergence model, hydrothermal time, mouldboard plough, subsoiler.

Introduction

Polygonum aviculare L. is one of the most widespread and studied weeds in the world (Holm *et al.*, 1997). It is a typical ruderal plant that also infests several crops, among those, Spanish winter cereals (Dorado *et al.*, 1999). The presence of *P. aviculare* is favoured by mouldboard ploughing (Dorado & López-Fando, 2006; Verdú & Mas, 2004), while conservation tillage systems, and especially direct drilling, decrease the *P. aviculare* populations with respect to conventionally tilled fields (Dorado *et al.*, 1999). In northeastern Spain, and more specifically in the Ebro Valley, the adoption of conservation tillage systems is increasing because of environmental benefits and savings in time and economic inputs (Sánchez-Girón *et al.*, 2007). However, this change is progressively altering the weed flora of cereal fields (Royo-Esnal *et al.*, 2011). The variation in the presence of weeds, and specifically of *P. aviculare*, in a field apparently is related to the formation or depletion of a persistent soil seed bank, which is highly affected by the soil tillage system (Verdú & Mas, 2004).

Although it is considered a summer annual weed (spring emerging) (Costea & Tardif, 2005), *P. aviculare* emergence can start in winter in northeastern Spain, thus competing with winter crops throughout the growing season. Seeds of *P. aviculare* must undergo a moist cold period (stratification) to germinate (Batlla *et al.*, 2009), which happens during autumn. Seed dormancy and germination are key components of the emergence process (Forcella *et al.*, 2000). These components of emergence have been widely studied for *P. aviculare*. Batlla & Benech-Arnold (2003, 2004) developed thermal time based models to describe the dormancy release of *P. aviculare* seeds. These models worked acceptably in irrigated fields, but not in rain-fed fields of winter cereals (Batlla & Benech-Arnold, 2004), where soil moisture is more variable than in irrigated fields. In fact, the emergence of annual species in systems where the upper layers of the soil profile remain continuously moist has been successfully predicted using models based only on thermal time (Dorado *et al.*, 2009). However, when soil water content is more variable over time and depth, hydrothermal time (HTT) based models usually have been best for predicting emergence, i.e. in rainfed winter cereal weeds (Royo-Esnal *et al.*, 2010).

Despite the numerous studies on seed banks in different tillage systems, and germination and dormancy release models, emergence patterns in contrasting tillage systems have not been studied for *P. aviculare*. In this work, the effects of four different tillage systems that are used in northeastern Spain were studied on a population of *P. aviculare*. To better understand the emergence pattern of the weed for management decisions, the population coming from the chisel plough system was used to develop a model of emergence, as this is the most frequently used tillage system in Spain. The developed model was tested in the other tillage systems to ensure its applicability in a wide range of soil management situations. Additionally, potential emergence periods were estimated for each season, similar to that reported by Guillemin *et al.* (2013), as functions of the base temperature (T_b) and base water potential (ψ_b) estimated during model development,.

Materials and Methods

Experimental site

Field trials were conducted from autumn to spring during three consecutive seasons (2008-09, 2009-10 and 2010-11) in an experimental cereal monoculture field that had been managed under four different tillage systems for 20 years when our experiment was initiated: direct drill (DD) with a no-till disc drill with 17-cm spaces between rows; subsoiler (SbS), with shanks spaced 35 cm apart and a working depth of 25 cm; chisel plough (ChP), with a working depth of 10-15 cm; and mouldboard plough (MbP), which inverted the soil to a depth of 25-30 cm. A roller was used for tilled systems to break clods before sowing. The field was located in Agramunt, Lleida, in northeastern Spain (41°48`N, 1°07`E). The soil was a Fluventic Xerocrept, 100-120 cm deep, with 30% sand, 52% silt, 18 % clay, 2.3 % organic matter and pH of 8.5. The two main weeds of the experimental site were *Bromus diandrus* Roth. and *P. aviculare*.

Cereal sowing dates were 15, 12 and 11 November in 2008, 2009 and 2010, respectively. Barley (*Hordeum vulgare* L.) cv. 'Hispanic' was sown in 2008 and 2010 and wheat (*Triticum aestivum* L.) cv. 'Artur Nick' in 2009. Each year crops were sown at 180 kg·seed ha^{-1} (400-450 plants·m^{-2}). Glyphosate was sprayed at 540 g ai ha^{-1} in DD and SbS systems one to six days before each sowing date. On 19 February 2009, a post-emergence tank mix of isoproturon plus diflufenican (1743 + 69 g ai ha^{-1}) was applied. In 2009-10, post-emergence weed control was accomplished by iodosulfuron-methyl sodium plus mesosulfuron-methyl (3 + 15 g ai ha^{-1} plus wetting agent) applied 6 March. In 2010-11, broadleaf and grass weeds were controlled post-emergence, respectively, by tribenuronmethyl plus metsulfuron-methyl (10 + 5 g·ha^{-1} plus wetting agent) and diclofop-methyl (900 g ai ha^{-1}) on 30 March. All plots were fertilized in March of each year with 48 kg N ha^{-1}.

Experimental design

The experiment was arranged in a randomized complete block design with three replications. Plot size was 6 x 50 m. One factor was considered, the type of tillage system. Emergence was sampled weekly by destructive counts in 10 fixed 0.33 x 0.33 m^2 quadrats per plot.

Weather data

Daily rainfall and maximum and minimum air temperatures were obtained from a standard meteorological station located at the experimental field.

Model development

The emergence model for *P. aviculare* was developed with data from ChP in seasons 2008-09 and 2009-10. This tillage system is used widely in the study area, and it provided high numbers of seedlings, which are needed for modelling purposes. 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):

$$\mathrm{HTT} = \sum (\mathrm{HT} \times \mathrm{TT})$$

where HT = 1 when $\psi > \psi_b$, otherwise HT = 0; and TT = $T - T_b$ when $T_c > T > T_b$, otherwise TT = 0. ψ is the daily average water potential in the soil layer from 2 to 4 cm; ψ_b is the base water potential for seedling emergence; T is the daily average soil temperature in the soil layer from 2 to 4 cm; T_b is the base temperature for seedling emergence (Royo-Esnal *et al.*, 2010), above which degree days can cumulate; and T_c is the ceiling temperature, below which degree days can cumulate.

The soil depth chosen for the HTT estimation was 2 to 4 cm because, after making several combinations of depths from 0 to 10 cm when estimating T_b and ψ_b, it gave the best accuracy when fitting the HTT model. Furthermore, this soil depth is in accordance with the fact that *P. aviculare* emerges mostly from the upper 3 cm of the soil (Froud-Williams *et al.*, 1984). With this method, HTT was accumulated only when the water potential and temperature conditions were higher than the base water potential and base temperature.

HTT was estimated using the Soil Temperature and Moisture Model (STM^2) (Spokas and Forcella, 2009). This method of estimating HTT with STM^2 has been used successfully in several works in northeastern Spain (García *et al.* 2013; Royo-Esnal *et al.*, 2010). STM^2 requires as input daily maximum and minimum air temperatures and daily precipitation, along with information on the geographical location and soil texture and organic matter. HTT were accumulated over days beginning on the date when the main rainfall occurred prior to the first sowing date. Similar to García *et al.* (2013) and Royo-Esnal *et al.* (2010), the base water potential and base temperature were determined iteratively calculating HTT using a set of water potentials (-2.0 MPa to -0.5 MPa, at -0.1 MPa intervals) and temperatures (-5º to +5º C at 0.5ºC intervals). Namely, the scale of HTT was changed by modifying the ψ_b and the T_b until the highest accuracy (R^2) was obtained for the relationship between HTT and cumulative emergence of *P. aviculare*. As seeds may enter secondary dormancy with temperatures above 20ºC (Kruk and Benech-Arnold, 1998), a ceiling temperature (T_c) had to be added for calculating the HTT. Estimation of this T_c was also made iteratively (12º to 20º at 1ºC intervals) together with ψ_b and T_b.

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

$$y = a\left[1 - e^{-(x-x_{50}+bln2^{1/c})/b)^{c}}\right]$$

where *y* is 0 if:

$$x < x_{50} - b * ln(2)^{(1/c)}$$

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_{50} is the HTT, in degree days, required to obtain

50% of emergence. To simplify this Weibull model, *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.

Readjustment of the emergence model

In order to make it more robust and widen the range of climatic situations where the model could work, the developed model was callibrated with data from ChP in the third season (2010-11). The callibration was performed iteratively, varying x_{50} so that the accuracy of the prediction was highest for the original data –first and second season- and the callibration data –third season-. Agreement between predicted and actual emergence values was determined with the root-mean-square error (RMSE):

$$RMSE = \sqrt{1/n \sum_{i=1}^{n} (x_1 - y_1)^2}$$

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

Cumulative emergence model validation and practical application

To evaluate application of the model to other tillage systems, root mean square error predictor (RMSEP), calculated as RMSE, for the model against different types of tillage (DD, SbS and MbP) examined during the three growing seasons were used to validate the emergence model and for discussing its practical application.

Estimation of annual emergence periods

Results of T_b and ψ_b, based on the work of Guillemin *et al.* (2013) to determine potential germination periods, allow the estimation of potential emergence periods for each of the three seasons. For this purpose, HTT must be estimated as before, and the following considerations from Guillemin *et al.* (2013) must be considered: Accumulation of HTT is stopped if daily temperature drops below T_b until it rises again; and HTT becomes nil if water potential drops below ψ_b. These periods were compared to and plotted against observed emergence in ChP, as well as cumulative HTT (without turning HTT nil when water potential drops below ψ_b).

Statistical analysis

Differences in values of total cumulative emergence between tillage systems and growing seasons were analysed with two way analyses of variance (ANOVA) and LSD post hoc (if significance appeared) with the program SPSS 15.0 for Windows (SPSS Inc., Chicago IL, USA).

Results

Climatic conditions

The three seasons differed considerably in terms of rainfall but not in temperature (Figure 1a). Total rainfall from September to harvest (June) in 2008-09 was 500 mm, while in 2009-10 it was 637 mm, and in 2010-11 only 190 mm. In addition to the rainfall quantity, number of rainy days also differed between the three seasons (64 in 2008-09, 77 in 2009-10, and 27 in 2010-11, Figure 1a), which is reflected in the soil water potential as long wet or dry periods (Figure 1b). Autumn-winter precipitation in 2008-09 and 2009-2010 was abundant (234 and 357 mm respectively from October to February), whereas only 13 mm of rain fell in 2010-11. Fortunately, such great natural variability in magnitudes of driving variables is highly desirable for the development of robust microclimate-based models.

Figure 1 near here

Differences among tillage systems

The first emerged seedlings were recorded on 28 November (2008-09), 30 December (2009-10) and 12 January (2010-11) (Figure 2). The periods of highest emergence, considered as increments of more than 10% of total emergence between sampling dates, lasted from 29 December to 20 February (2008-09), 11 January to 2 of March (2009-10), and from 12 January to 21 March (2010-11). No emergence was observed after 20-21 March (2008-09 and 2009-10), and 14 April (2010-11) (Figure 2).

Figure 2 near here

Cumulative emergence was highest in SbS in the three growing seasons (significant only in 2008-09 and 2009-10), intermediate in ChP and MbP, and consistently lowest in DD (Figure 2). There was a decreasing trend in emergence from 2008-09 to 2010-11 in the four tillage systems. This reduction, in terms of percentage, was highest in DD (91% from 2008-09 to 2010-11), followed by ChP (88%), MbP (84%) and lowest in SbS (77%) (data not shown). Despite this high reduction from the first to the third season in DD, differences were not significant across years (Figure 2), probably because densities in DD were very low even in the first year of the experiment.

Seedling emergence model development

The emergence model (Weibull function) calculated using data from ChP in 2008-09 and 2009-10 is shown in Figure 3. In both seasons, emergence was characterized by a quick flush followed by a more gradual pattern. The model was calibrated with data from ChP in season 2010-11. To optimize emergence model fit, a unique base temperature, ceiling temperature and base water potential were required. The best fitting T_b was determined to be -2 ºC, the best fitting T_c was 17ºC and the best fitting ψ_b was -3.5 MPa (R^2 = 0.88). Estimates of the variables b, c and x_0 fitted to HTT for *P. aviculare* are 251 ±45, 1.33 ±0.36 and 645 ±13.4, respectively. The RMSE was of 12.1 for 2008-09, 9.8 for 2009-10 and 9.9 for 2010-11 (data not shown), and 10.3 for the three seasons together (Figure 3).

Figure 3 near here

Validation in other tillage systems

The emergence model successfully predicted the emergence in most tillage systems and seasons with completely different weather situations (Figure 4). The accuracy of this model developed for the emergence of *P. aviculare* was very good in three situations (values of RSMEP between 5-10), good in another three (RMSEP between 10-15) and insufficient in the last three situations (RMSEP > 15). Even in these latter three comparisons, however, the model still accurately depicted the times of initiation and culmination of emergence, which can be important phenological events in terms of weed management.

Figure 4 near here

Estimation of annual emergence periods

The periods estimated for the emergence of *P. aviculare* show an almost complete overlap with observed emergence in ChP at each sampling date (Figure 5). The 2008-09 and 2009-10 seasons show similar main estimated periods that start in January and end in May, with similar cumulate HTTs. Meanwhile, 2010-11 had more emergence periods with less cumulated HTT and more spread of emergence over time (Figure 5). As a consequence, emergence flushes appeared earlier in 2010-11 and lasted longer and ended later. This means that as much as 20% of the emerged seedlings would have not been covered by the developed model when predicting 90% emergence (Figure 5).

Figure 5 near here

Discussion

Model of emergence

Several models now exist to predict weed emergence. These can be very useful whether used alone, or combined with other models to assist with choosing management options (Batlla *et al.,* 2009; Batlla & Benech-Arnold, 2007; Boddy *et al.*, 2012; Colbach *et al.*, 2006; Onofri *et al*., 2011).

In the current work, field emergence of *P. aviculare* was modeled successfully and contrasted in differently managed soil treatments. This model describes not the amount, but the proportion of emergence that occurs at various hydrothermal times. The cumulative emergence of *P. aviculare* followed the typical sigmoidal curve in all tillage systems, resulting from the normal emergence distribution of the seedlings over hydrothermal time. The only season when emergence acquired a more linear shape in all the tillage systems was 2010-11, when a prolonged drought occurred from November to March. This drought revealed a clear dependence of emergence rate on environmental conditions (i.e., soil water potential) rather than on soil management. Moreover, when the model did not describe emergence with high accuracy (RMSEP >15), the reason likely was due to the very low numbers of seedlings observed (< 25), which was particularly evident in DD.

Literature values for T_b and ψ_b for *P. aviculare* germination are 0ºC (Kruk & Benech-Arnold, 1998) and between -0.27 and -0.58 MPa (Batlla & Benech-Arnold, 2004). However, these were estimated at -2ºC and at -3.5 MPa for emergence in the current work. Several reasons explain these differences: First, the studied processes are not the same, as the former are for seed germination, whereas we examined seedling emergence. The temperature and moisture requirements for radicle protrusion may differ from those for hypocotyl and root elongation. Second, stratification conditions in fields differ from those in laboratory situations. Third, different geographical origins of populations (Argentina vs. Spain) might have different temperature and moisture requirements as occurs in other plant species (Guillemin *et al.*, 2013). Fourth, establishing the T_b at -2ºC does not mean that *P. aviculare* is able to emerge at temperatures below 0ºC, but that temperatures can arise to positive values for some brief time during the day. Indeed, *P. aviculare* commonly emerges during March in Morris, Minnesota (cold temperate climate) when minimum, mean, and maximum daily air temperatures are -6.9°, -2.2°, and 2.6°, respectively. Some physiological activity likely occurs during brief daily periods above 0°. The fact that the emergence periods, estimated as Guillemin *et al.* (2013) for germination periods, coincide with our observed emergence events (Figure 5) verifies that the estimated T_b and ψ_b are close to their real values.

Effect of different tillage systems on population dynamics

By end of the three experimental seasons in 2010-11, the accumulated effects of tillage systems were over 23 years. Thus, equilibrium of the seedbank of *P. aviculare* likely was achieved over this time.

Although a simulation with the FlorSys program of the responses of *P. aviculare* populations managed with different tillage tools showed no differences (Colbach *et al.*, 2014), the lower emergence in DD in our study was distinct and is in agreement with other works where highest seed bank (Dorado *et al.* 1999) and seedling densities (Verdú & Mas, 2004) of *P. aviculare* were seen in tilled systems. Furthermore, the association of this weed to autumn tilled fields is well known (Chancellor, 1985).

Other factors also may have affected the decrease of emergence over time. This includes shallow burial depths of seeds in no-till (DD) systems (Benvenuti, 2007). This may have led to more seeds exposed to low winter temperatures, as well as to more light, which promotes dormancy release (Batlla & Benech-Arnold, 2005). In contrast, in the other tillage systems, after 20-23 years of soil disturbance, seeds would have been distributed uniformly in the soil profile down to the ploughing depth (Grundy *et al.*, 1999; Colbach *et al.*, 2006). Deeply buried seeds (> 8 cm) usually do not contribute to seedling emergence (Zhang *et al.*, 1998). This may allow the formation of a permanent seedbank, and soil disturbance would bring a proportion of deeply buried seeds to shallower depths every year, possibly allowing them to germinate and emerge.

Conn & Werdin-Pfisterer (2010) observed, after 25 years that there were no viable seeds of *P. aviculare* at a depth of 2 cm, but 3% of seeds still remained viable at a depth of 15 cm. In our experiment, after 23 years with the same management, in DD most seedlings must come from recently produced seeds. This indicates that seed banks in ChP and MbP are much more persistent than in the other two tillage systems, and that emergence in these systems will be more uniform throughout seasons.

Finally, the presence of *P. aviculare* was lowest in DD, and this tillage system is not a constraint in terms of cereal yield. Accordingly, it seems the best tillage system to use to manage this weed. Moreover, control of other weeds was also successful with DD, e.g., *Bromus diandrus* (García *et al*., 2014), although choice of sowing date is critical for this purpose and may progressively change the weed flora with the entrance of other less common weed species (Royo-Esnal *et al.*, 2011).

Conclusions.

The emergence of *P. aviculare* is determined by both soil temperature and soil moisture. With these two factors, a model that describes the relative proportions of emerging seedlings of this weed was developed and demonstrated to be robust and reliable, as it was validated in three different soil management systems. This model can be a useful tool to improve the management and the control of *P. aviculare* in dryland cereal fields of semiarid regions. Direct drilling was the only tillage system of four that were tested that was able to control *P. aviculare* culturally and reduce infestation to very low levels. Therefore, the decision to till soil is an important consideration for managing *P. aviculare* seed banks.

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Fig. 1 Weather conditions of seasons 2008-09, 2009-10 and 2010-11 (a) and estimated soil temperature and soil water potential between 2 and 4 cm for the same dates (b) with the STM^2 program.

Fig. 2 Cumulative emergence of *Polygonum aviculare* (seedling·m^{-2}) in the three years of the experiment: closed circles, direct drill (DD); open circles, subsoiler (SS), closed triangles, chisel plough (ChP) and open triangles, mouldboard plough (MbP). Different letters show significant differences in total cumulative emergence: capital letters, differences between tillage systems in each season; small letters, differences between years within a tillage system.

Fig. 3 Observed cumulative emergence of *Polygonum aviculare* in 2008-09 (closed circles) and 2009-10 (open circles) in ChP and representation of the model developed with these data as a function of hydrothermal time (HTT). Data of cumulative emergence ChP in 2010-11 (shaded circles) were used to calibrate the model considering the lowest Root Mean Square Error (see graph). Emergence fitted using the Weibull function (see formula).

Fig. 4 Hydrotermal seedling emergence model application for *Polygonum aviculare* in differents tillage systems (direct drilling, DD; subsoiler, SbS; and moldboard plow, MbP) in Agramunt (Spain) for three growing seasons 2008-09, 2009-10 and 2010-11. RMSEP is shown. Lines represent predicted emergence. Symbols represent observed emergence.

Fig. 5 Estimated periods of emergences for each of the three studied seasons in ChP (above, 2008-09; middle, 2009-10; bottom, 2010-11). Straight lines: cumulative HTT and estimated emergence periods based on Guillemin *et al.* (2013). Long dashed lines: cumulative HTT without considering nil values. Bars: percentage of the total observed emergences each sampling date. Short dashed lines indicate the cumulate HTT for the beginning of the emergence (455 HTT) and for the 95% of cumulate emergence (1019 HTT) according to the model developed in this article. Black arrows indicate the herbicide application date each season.

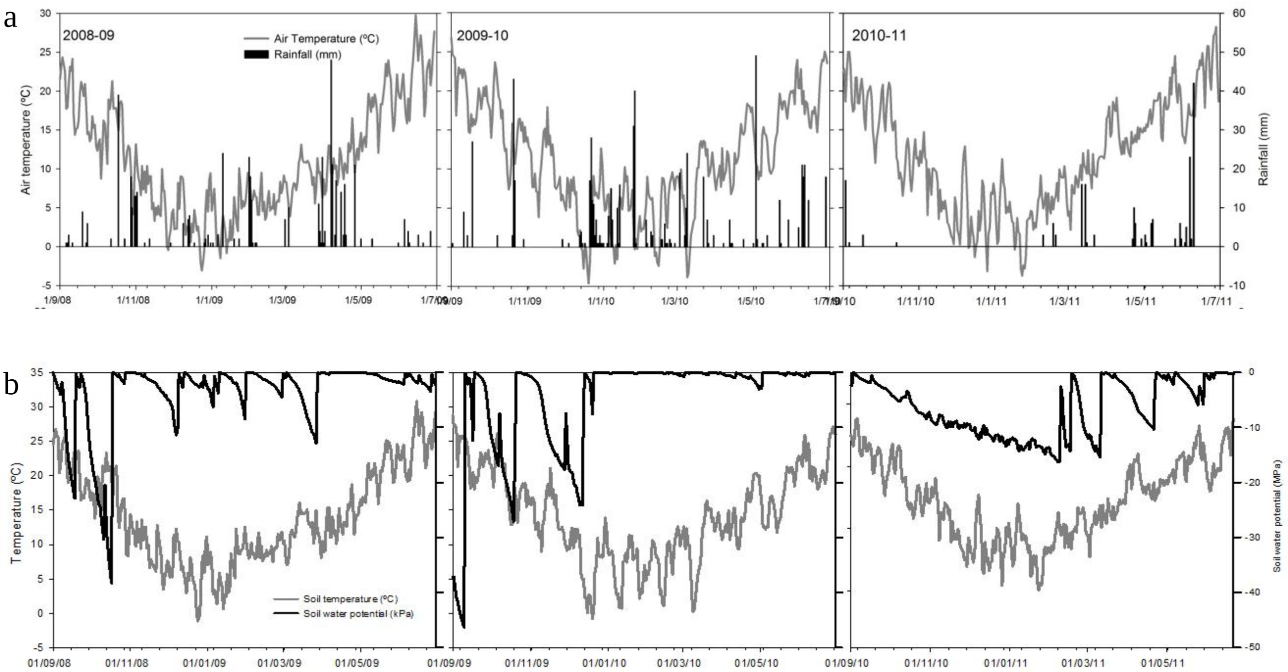

Figure 1. Weather conditions of seasons 2008-09, 2009-10 and 2010-11 (a) and estimated soil temperature and soil water potential between 2 and 4 cm for the same dates (b) with the STM^2 program.

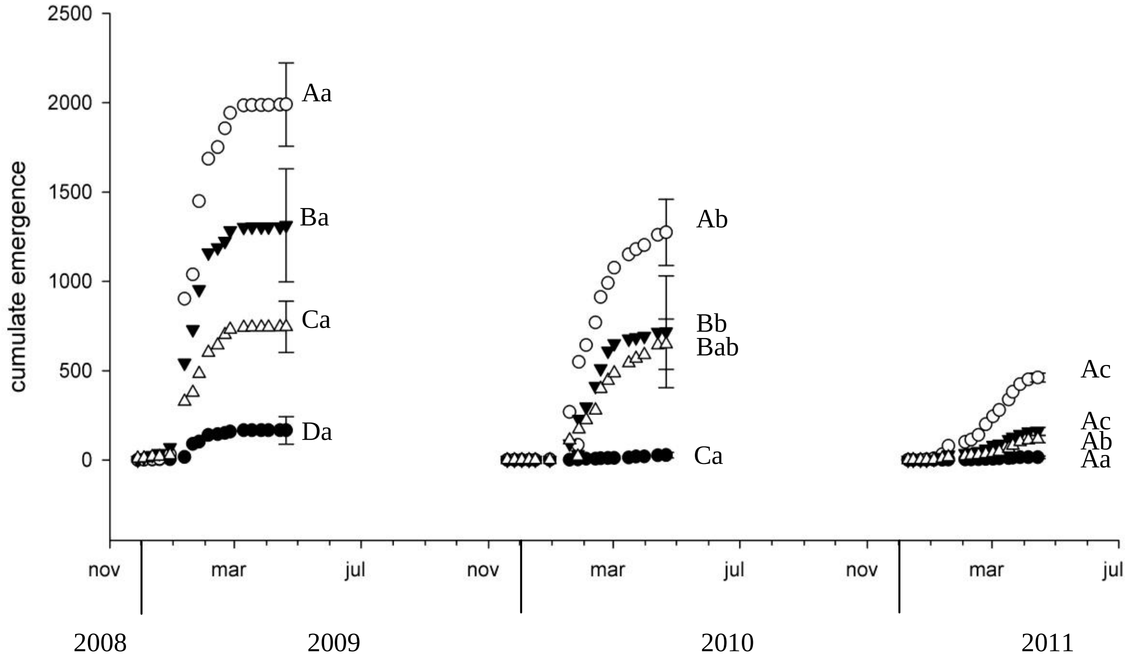

Figure 2. Mean cumulative emergence of *Polygonum aviculare* (seedling·m^{-2}) in the three years of the experiment: closed circles, direct drill (DD); open circles, subsoiler (SbS); closed triangles, chisel plough (ChP); and open triangles, mouldboard plough (MbP). Standard error is provided only for the last sampling date for clarity of the graph. Different letters show significant differences in total cumulative emergence: capital letters, differences among tillage systems in each season; small letters, differences among years within a tillage system.

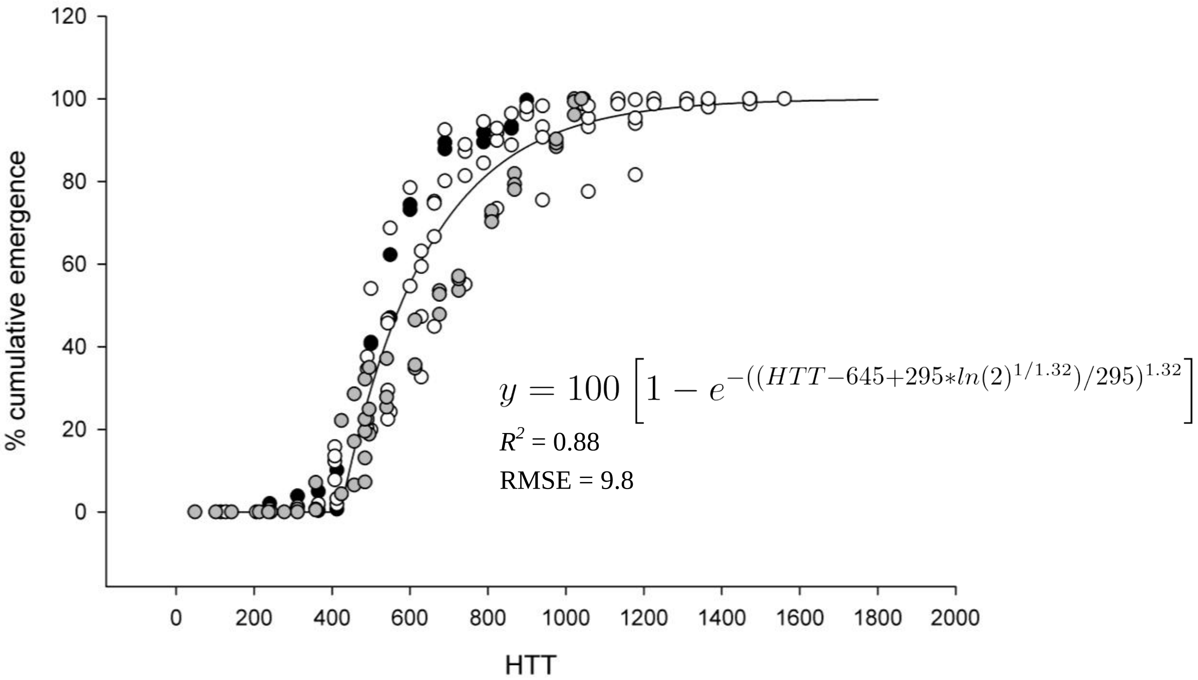

Figure. 3. Observed mean cumulative emergence of *Polygonum aviculare* in 2008-09 (closed circles) and 2009-10 (open circles) in ChP and representation of the model developed with these data as a function of hydrothermal time (HTT). Data of cumulative emergence ChP in 2010-11 (shaded circles) were used to calibrate the model considering the lowest Root Mean Square Error (see graph). Emergence fitted using the Weibull function (see formula).

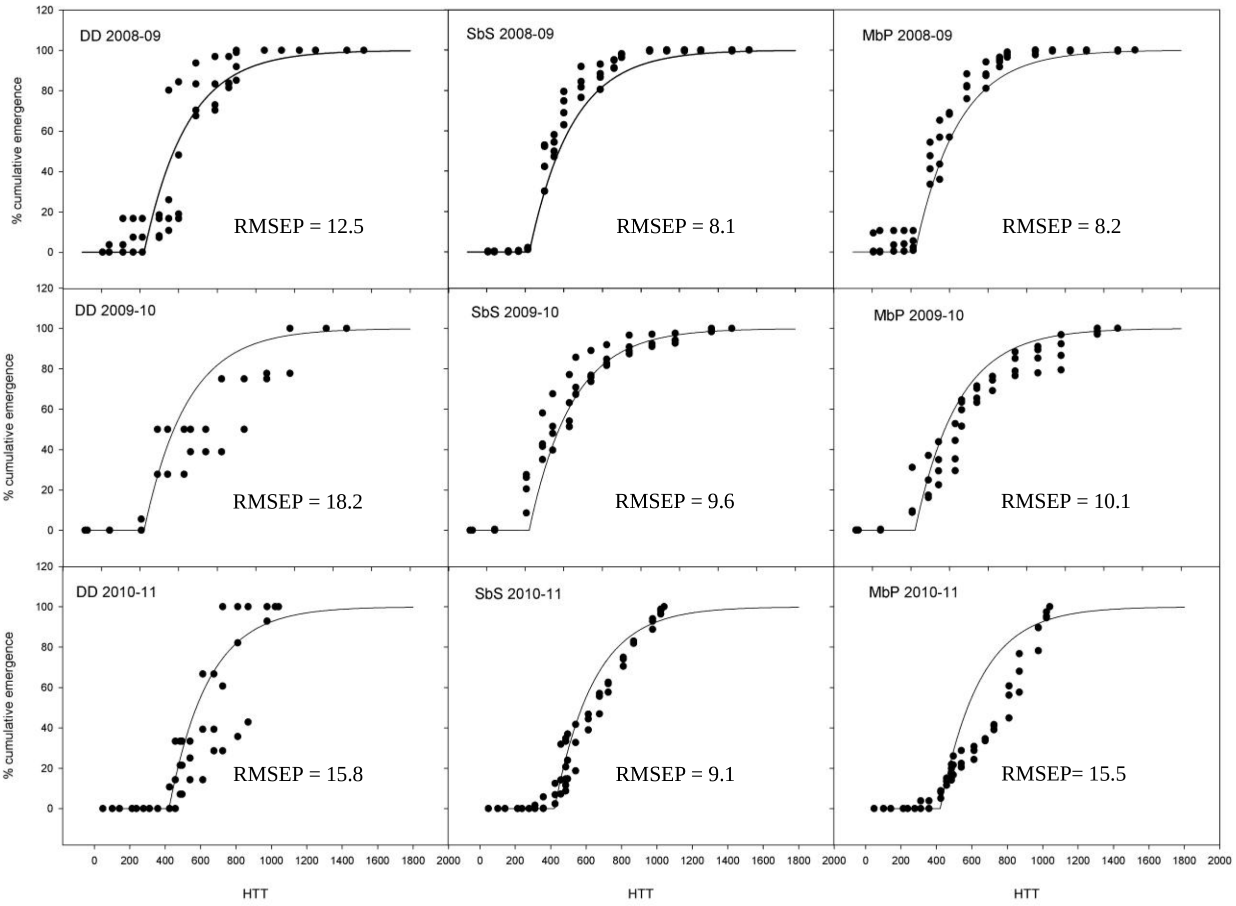

Figure 4. Hydrotermal seedling emergence model validation for *Polygonum aviculare* in differents tillage systems (direct drilling, DD; subsoiler, SbS; and moldboard plough, MbP) in Agramunt (Spain) for three growing seasons 2008-09, 2009-10 and 2010-11. RMSEP is shown. Lines represent predicted emergence. Symbols represent mean observed emergences per replication.

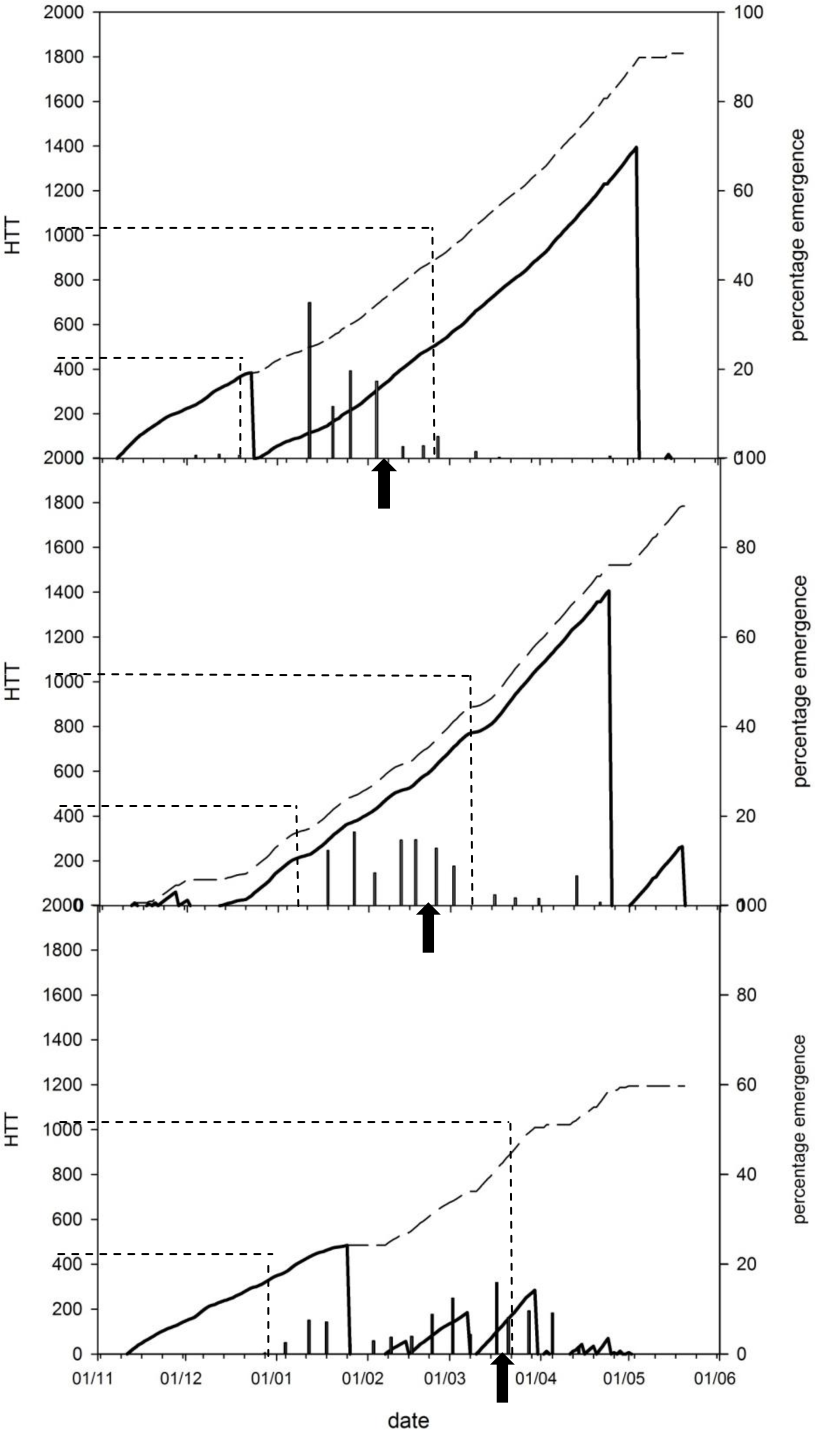

Figure 5: Estimated periods of emergence for each of the three seasons (top, 2008-09; middle, 2009-10; bottom, 2010-11). Solid lines: cumulative HTT and estimated emergence periods based on Guillemin *et al.* (2013). Long dashed lines: cumulative HTT without considering nil values. Bars: percentages of the total observed emergence at each sampling date. Short dashed lines indicate the cumulate HTT for the beginning of emergence (455 HTT) and for 95% of cumulative emergence (1019 HTT) according to the model developed in this article. Black arrows indicate the herbicide application date each season.