



Modelling seedling emergence of *Amaranthus retroflexus* affected by soil depth

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Abstract

Aim of study: To determine and quantify the effect of seed burial depths on the seedling emergence pattern of *Amaranthus retroflexus* in field conditions.

Area of study: West of Iran (Ilam).

Material and methods: The seedling emergence of *A. retroflexus* was studied in an outdoor pot experiment, burying the seeds at 0, 2, 4, 6 and 8 cm in the soil in Ilam (Iran) in two consecutive years, 2010 and 2011. Different models were tested to predict the cumulative seedling emergence, and the log logistic model was found to be the best for this *A. retroflexus* population. Newly estimated T_b values, slightly different each year, but lower than those of the references, were estimated and set at 2.6 °C and 0 °C in 2010 and 2011, respectively.

Main results: The seedling emergence in the west of Iran take place over a period from early February to late May. The level of seed dormancy can be reduced during autumn and winter burial in the soil or after a dry storage. Seed dormancy reduction resulted in a lower base temperature for germination/emergence followed by increase of the seedling emergences. Moreover, light in the soil surface and higher fluctuation in temperature at shallower soil depths may stimulate the seed germination and seedling emergence of *A. retroflexus*.

Research highlights: Total emerged seedlings and emergence pattern are affected by soil depth and the level of dormancy. The results obtained in this study can be used to optimize the timings of the weed management activities.

Additional key words: dormancy induction; emergence timing; fecundity; weed control.

Abbreviation used: GDD (growing degree days); HT (hydrotime); HTT (hydrothermal time); RMSEP (root mean square error predictor); STM2 (Soil Temperature and Moisture Model); VI (vigor index); ψ_b (base water potential).

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Introduction

Amaranthus retroflexus L. (redroot pigweed) is an annual C₄ weed species spread worldwide (Weaver & McWilliams, 1980), where it invades maize, soybean, forages and horticultural crops (Holm et al., 1997; Costea et al., 2004). This species presents a large fecundity, producing seeds that can remain viable in the soil for up to 40 years (Weaver &

McWilliams, 1980) due to their seed dormancy status (Baskin & Baskin, 1977), and thus, it is able to build a persistent seed bank. *A. retroflexus* has been reported to have allelopathic effects on some weeds and crops (Athanasova, 1996), and it is also known as an alternative host for a number of crop pests, diseases and the parasitic weed *Orobancha ramosa* (Weaver & McWilliams, 1980). All these aspects have made of *A. retroflexus* a main weed to be controlled in many crops.

Weed seedling emergence models contribute to predict their field emergence (Forcella et al., 2000; Taab & Andersson, 2009a). The number and timing of seedling emergence are the most important characteristics describing emergence patterns of weeds (Vleeshouwers, 1997), and considering the response of weeds to burial depths is crucial for developing predictive tools (Forcella et al., 2000), which will optimize the timing of weed control measures (Grundy, 2003). In this sense, soil disturbances can be adapted to affect the emergence of seedlings and manage the weed seed banks. For instance, deeply buried seeds may not be able to emerge while zero tillage may promote greater emergence of species that require light for germination (Chauhan & Johnson, 2009).

Emergence timing of weeds is affected by several external (environmental) and internal (biological) factors, and their interactions during seed maturation (Omami et al., 1999). *A. retroflexus* seeds present primary dormancy that can be reduced during winter and induced into secondary dormancy during summer months (Egley, 1989; Kępczyński et al., 1996), which may go through seasonal cycles of dormancy and non-dormancy states. Release of seed dormancy in *A. retroflexus* either by stratification or by autumn–winter burial has also been reported (Kępczyński & Sznigir, 2013) suggesting the presence of physiological seed dormancy (Baskin & Baskin, 2004).

Burial depth of seeds in the soil profile was shown to enhance seed dormancy and longevity in *A. retroflexus* (Omami et al., 1999). The seed longevity in this species could range from several months up to 40 years, depending on burial depth (Schonbeck & Egley, 1980; Burnside et al., 1996), while longevity in the soil could be greater in cooler climates (Costea et al., 2004).

Environmental factors required for seed germination, such as temperature, moisture and light, can also affect seed fate in the soil (Stoller & Wax, 1974), while they vary within the soil profile (Stoller & Wax, 1973; Sukhbaatar et al., 2019). Temperature is a major factor affecting seedlings' emergence pattern (Taab & Andersson, 2009a, 2009b). On the other hand, even if less than 1% of light penetrates a few millimeters into the soil (Woolley & Stoller, 1978), it significantly affects seeds placed at very shallow depths or at the soil surface.

Seeds of *A. retroflexus* germinate better at temperatures between 25 and 35 °C (Ghorbani et al., 1999), although more than 60% of germination can be obtained with temperatures of up to 40 °C under light conditions (Weaver & McWilliams, 1980; Ghorbani et al., 1999), while alternating temperatures may also stimulate seed germination (Guo & Al-Khatib, 2003). The base temperature (T_b) required for emergence has been set at different levels based on the location of the study. Gardarin et al. (2009) established it at 4 °C for a French population, while populations from Italy required a T_b between 12.1 and 12.3 °C (Masin et al., 2010), and Werle et al. (2014) suggest a T_b of 9 °C in North America. These results show the high variability

for a T_b establishment between populations and, hence, the need of developing different emergence models for each agroclimatic region, as suggested by Sousa-Ortega et al. (2020).

Seedling emergence was also found to be affected by soil amendment (Amisi & Doohan, 2010), depth, and soil type (Ghorbani et al., 1999). The number and rate of seedling emergence was shown to decrease with increasing depths of burial in many species (Benvenuti, 2003). Seedlings of *A. retroflexus* emerge better from shallow depths of 0 to 2 cm, while they were unable to emerge when buried deeper than 4 cm (Ghorbani et al., 1999), although some authors increase this depth to 6.4 cm (Webb et al., 1987). However, to our knowledge, there is no report on the effect of burial depth on seedling emergence pattern of the species over time in different soil depth.

In the last two decades, there has been an increased tendency towards optimizing the timing for applying weed management tools. For this reason, many studies have been published to understand the emergence behavior of weeds. On the other hand, the factors affecting the emergence of weeds change with the seed burial depth (Stoller & Wax, 1973; Sukhbaatar et al., 2019). Therefore, there is a need to understand how these control the time and extent of seedling emergence in the field. Thus, the objective of this study was to determine and quantify the effect of seed burial depths on the seedling emergence pattern of *A. retroflexus* in field conditions.

Material and methods

Seed collection

Seeds were collected in early January 2010 from mature plants growing in a research station (33° 38' 17" North, 46° 25' 50" East) in Ilam, Iran. They were cleaned and stored at constant 5 °C until set of the experiment. These seeds were used for the experiments conducted in both 2010 and 2011.

Sowing seeds in pots outdoors

Pots of 18-cm in diameter and 18-cm in height were prepared for sowing the seeds by filling and packing them with sieved soil extracted from the experimental field (42% clay, 24% silt and 34% sand; pH 7.85, and organic carbon 1.2%) to nominated depths in each pot. The soil was previously bulked under a plastic film cover for 4 months to enhance decay of the included weed seed in the soil. In mid-January 2010, pots were sunk into the ground with their rims protruding 5 cm above the ground level. The bottoms of the pots were opened with several holes to ensure proper contact with the surrounding soil environment.

The experiment was repeated in mid-January 2011 using a clay soil (40% clay, 26% silt and 34% sand; pH 7.60 and organic carbon 3.6%). Any possible contamination of seeds in the soil was checked using four unsown pots.

One hundred seeds were evenly distributed in each pot at five depths (0, 2, 4, 6 and 8 cm). To achieve a desirable depth, the pots were first filled and compacted with wet soil to desired depths. Thereafter, the seeds were sown and then the pots were filled and packed with soil until the surface was 5 cm below the rim. The pots were covered with a fine mesh to prevent any possible seed predation, and finally they were randomly distributed in a randomized complete block design with four replications.

Seedling emergence

The pots were surveyed for emergence every day from sowing to June, when no more emerged seedling was observed in both years. Every emerged seedling was counted and removed to avoid double counts in the following sampling day. The pots were watered thoroughly (0.5 L per pot each time) when needed, due to decreased precipitation; using a hand sprinkler from early to late May in both years. Seedling removal was done avoiding any soil disturbances.

Soil temperature and moisture

Soil temperature was recorded hourly at every sowing depth during the experiment using one temperature logger (iButton 1-Wire Thermochron DS1921G-F5, Dallas Semiconductor, Inc. USA) per sowing depth. Soil temperature was not recorded from 10 to 21 February 2010; therefore, the soil temperature for this period was estimated using the Soil Temperature and Moisture Model (STM²) (Spokas & Forcella, 2009) and weather data from a nearby meteorological station.

For the application of the already developed emergence models and, if necessary, new model development, soil temperature was accumulated in growing degree days (GDD) over time following Gupta (1985):

$$GDD = \sum (T_t - T_b) \quad [1]$$

where $GDD = 0$ when $T_t < T_b$ or $T_t > T_c$; T_t is the daily average soil temperature at the corresponding burial depth (0, 2, 4, 6 or 8 cm) of the seeds in day t ; T_b is the base temperature for accumulating degree days for seedling emergence for *A. retroflexus*; and T_c is the ceiling temperature over which degree days cannot be accumulated.

The GDD were then corrected with the soil moisture level (hydrotime, HT), based on Roman et al. (2000), to estimate hydrothermal time (HTT):

$$HTT = \sum (GDD * HT) \quad [2]$$

where $HT = 1$ when $\psi > \psi_b$, otherwise $HT = 0$; and GDD is obtained in Eq. [1]. Water potential (ψ) is the daily average water potential in the soil layer at 4 cm depth; ψ_b is the base water potential (in MPa) for seedling emergence (Martinson et al., 2007; García et al., 2013). With these formulas, GDD are accumulated only when soil moisture and temperature conditions are over the base water potential and the base temperature, respectively. The 4 cm depth was chosen for water potential for those seedlings above this depth (0 and 2 cm), because they can elongate radicles to a certain depth to absorb enough water for emergence (Royo-Esnal et al., 2019), while for those buried from 4 to 8 cm, which are not dried as much as the upper soil layers, the moisture of their corresponding burial depth was considered (4, 6 or 8 cm). The GDD and HTT were estimated using the STM² (Spokas & Forcella, 2009), which estimates the temperature and moisture of the soil at each centimeter of depth. The sowing date of each season was chosen as the starting point for GDD and HTT accumulation; the same T_b , estimated for the already published models, was considered for their application; ψ_b was determined by modifying the value until the highest accuracy (R^2) was obtained for the relationship between HTT and cumulative seedling emergences (Royo-Esnal et al., 2010).

Statistical analysis

Two-way analysis of variance (ANOVA) was applied to the observed total emergence, with year and burial as fixed factors, using the GLIMMIX procedure of SAS 9.4 (SAS Institute Inc., Cary, NC, USA). The proportion of emerged seedlings was tested as a categorical variable, assuming binomial distribution and logit link function. Standard error of mean (SEM) was calculated using the LSmeans statement with ilink function in the GLIMMIX procedure with account for the assumed binomial distribution.

The observed cumulative emergence, based on GDD, was compared to the already developed emergence model for *A. retroflexus* from Werle et al. (2014), who used a T_b of 9 °C:

$$y = 100 \times \left\{ 1 - e^{\left[-e^{(-12.8519 \times GDD^{1.9661})} \right]} \right\} \quad [3]$$

where y is the percentage of emergence.

The predictive capacity of this model to describe the emergence pattern of our data at all depths was explored with the root mean square error predictor (RMSEP):

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

where x_i is the observed cumulative emergence and y_i is the predicted emergence by model [4]. Further, alternative

T_b (using estimates from Masin et al., 2010 and additional selected values down to 0 °C) were evaluated. Thereafter, concluding that the predictive capacity of the model [3] was low regardless the chosen T_b , a new model was developed, based on a logistic function [5], considering the emergence results of 2011 at all depths:

$$y = \frac{a}{1 + ab \left(\frac{x}{x_0} \right)^b} \quad [5]$$

where y is the percentage of emergence, x is the time expressed as HT, and a , b and x_0 , are empirically derived constants: a , is the maximum percentage of emergence, b is the emergence rate every HTT degree, and x_0 is the HTT required to reach 50% of emergence considering a as the maximum emergence percentage.

Data from year 2011 were chosen for the development of the new model because the number of emerged seedlings was higher than that in year 2010, which were used for the validation of this model with the RMSEP [Eq. 4]. This new model was calibrated and validated with data from 2010 and readjusted to the original data from 2011 to ensure that its accuracy was still good.

Results

Climatic variables

Daily mean air temperature and precipitation during the experiments are reported in Fig. 1. The total precipitations were 288.4 mm and 189.5 mm during the experiments, in 2010 and 2011 respectively. The minimum daily mean temperatures were 4.2°C and 1 °C, recorded on 26 February 2010 and 12 February 2011, respectively; while the maximum daily mean temperatures were 25.6 °C and 23 °C, recorded on 19 May 2010 and 18 May 2011.

The daily mean soil temperature was similar at all depths. However, daily temperature fluctuation (difference between daily maximum and minimum temperatures) was higher at the soil surface and decreased with increasing depths (data not shown). For example, the greatest daily temperature fluctuations were observed on 15 March 2010, which were of 24.5 °C at 0 cm and 7.5 °C at 8 cm.

Seedling emergence

In 2010 the mean seedling emergence for all sowing depths was 9.8%. Emergence was first observed on 13 February at all depth sowings, except in seeds sown at 6 cm (Fig. 2A). The emergence period lasted until 9 May, with main flushes occurring at the end of March and early April (Figs. 2A and 2B). For seeds placed on the soil surface,

flushes were observed when the minimum daily temperature did not drop below 10 °C, and with about 25 °C of daily fluctuation between daily minimum and maximum temperatures. For the rest of the depths, seedling emergence took place almost over the same period of time, reaching 50% of emergence at about the same date (end of March), except for seeds buried at 2 cm, which were delayed until mid-April (Fig. 2A). A decreasing number of emerged seedlings was observed with increasing depth (Table 1).

In 2011, seedling emergence increased with respect to 2010 (21.0%). It started in seeds at 0, 2 and 6 cm on 17 February and ended on 24 May, with the highest flush occurring between 7 and 21 April (Fig. 2B). Fifty percent of emergence occurred between 25 and 31 March at 4 cm depth, while it was delayed to 7-10 April at 0 and 2 cm. In this period, minimum temperatures were over 14 °C, and day-night fluctuation was almost 25 °C on the soil surface. Like in 2010, fewer seedlings emerged with increasing depths.

The emergence of the *A. retroflexus* seedlings varied from one year to the next (Table 1), and between burial depths in both seasons. The number of emerged seedlings was significantly higher in 2011 than in 2010, and at the soil surface than in the rest of the burial depths.

Seedling emergence pattern based on GDD

The emergence pattern of the present study could not be described by the model from Werle et al. (2014). When the model from these authors was subjected to the emergence data at all depths in 2010 and 2011 (Figs. 3 A and B) based on GDD estimated with a T_b of 9 °C, it failed to describe their emergence. In contrast, considering new logistic emergence models with this same T_b , they could success-

Table 1. Total seedling emergences of *Amaranthus retroflexus* in 2010 and 2011 at all soil depths, and analysis of variance to test the effect of soil burial depth and year on total seedling emergence of *Amaranthus retroflexus*. Values in parentheses represent $\pm$ SEM. Upper case letters denote differences between years; lower case letters denote differences between sowing depths.

Depth	Year	
	2010	2011
0 cm	32.9 (8.0) Aa	40.4 (8.7) Aa
2 cm	8.7 (3.1) Ab	14.7 (4.7) Ab
4 cm	2.4 (1.1) Bb	21.6 (6.2) Ab
6 cm	2 (0.9) Ab	13.8 (4.5) Ab
8 cm	3.2 (1.4) Ab	14.6 (4.7) Ab
Mean	9.8 (2.9)	21.0 (5.8)

Effect	DF	F Value	P > F
Year	1	32.72	<0.0001
Soil depth	4	12.81	<0.0001
Year*Soil depth	4	2.92	0.0398

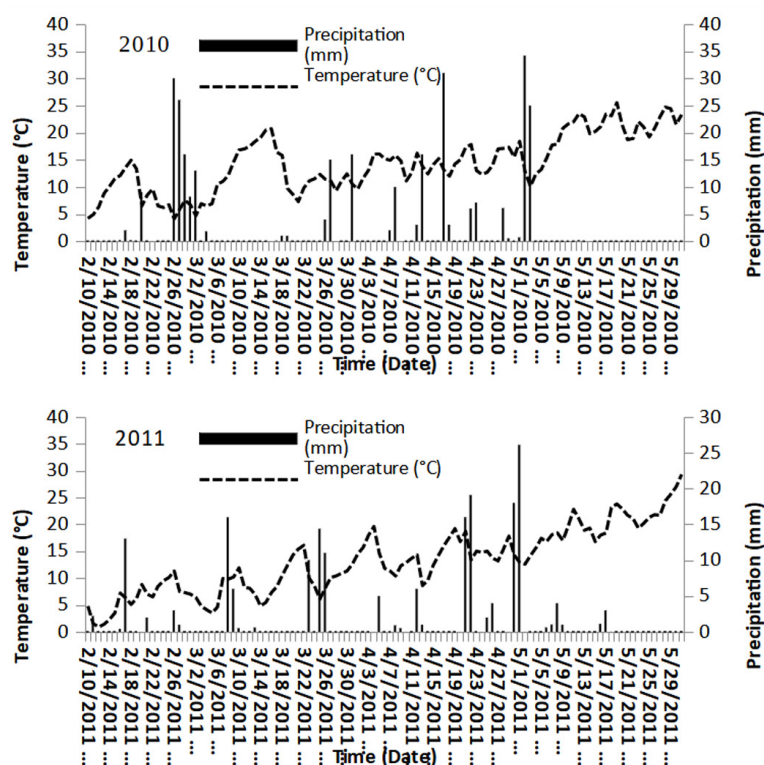


Figure 1. Daily mean air temperature and precipitation during the experiments

fully be fitted to the data in both seasons, with values in 2011 being $a = 100$; $b = -1.5375$; $x_0 = 20.2307$; $R^2 = 0.92$, and average RMSEP value for all depths of 12.3, varying these values from 8.6 at 2 cm up to 17.5 at 8 cm (Fig. 3A), and in 2010 being $a = 100$, $b = -2.0725$; $x_0 = 124.8438$; $R^2 = 0.87$, and a similar average RMSEP value to 2011 (12.3), values ranging between 8.9 at 4 cm and 14.7 at 6 cm.

Emergence model

The lowering of the T_b value contributed to lower RMSEP values, both average and for each of the burial depth (Fig. 4), thus gaining accuracy for the predictive capacity of the model, which was also reflected in the increase of the R^2 from 0.90 at $T_b = 7.9$ °C up to 0.95 at $T_b = 0$ °C, and decreasing the sum of squares from 79897 to 38438 between these two T_b .

The emergence of this *A. retroflexus* population was successfully modelled with a HTT-based logistic function. The T_b , T_c and ψ_b established for the HTT accumulation were 0 °C, 25 °C and -0.4 MPa, respectively. The function parameters were established at $a = 95.7$, $b = -9.67$ and $x_0 = 380.7$.

Calibration and validation of the model

The new emergence model was calibrated and validated with data from the same population sown in 2010. The val-

idation with the new estimated T_b at 0 °C was unsuccessful at all depths (RMSEP > 15; Royo-Esnal et al., 2010) (Fig. 5A), with an average value of 24.1 (Table 2) and values that varied from 17.8 at 8 cm up to 30.3 at 2 cm depth. The increase of the T_b value from 0 °C to 2.6 °C, and the calibration of the parameter b from -9.67 to -5.11, allowed a better accuracy of the model (Fig. 5B); the average RMSEP value (14.6, Table 2) was successful, according to Royo-Esnal et al. (2010), and at the burial depth where more than 10% of the sowed seeds showed emerged seedlings, the resulting RMSEP values was very good (7.3 at 0 cm, Table 2). This calibration made the model less accurate for the data of 2011. Despite this, the average RMSEP was still good (11.2) with values ranging from 7.5 at 2 cm up to 13.7 at 8 cm (Table 2).

Discussion

The results suggest that the seedlings of *A. retroflexus* have the potential to emerge over an extended period of some months, similar to Burnside et al. (1981) and Costea et al. (2004), which complicates the management of this weed in the fields. In the present study, the daily minimum soil temperature about 10 °C to 14 °C with day-night fluctuation of 25 °C coincided with flushes of *A. retroflexus* although sporadic emergence outside this range also occurred. Ghorbani et al. (1999) observed that temperatures between 25 and 35 °C are the optimum for the germina-

Table 2. Root mean square error predictor (RMSEP) values for the emergence of *Amaranthus retroflexus* seedlings at each seed burial depth. The initial logistic function parameters were $a = 95.7$, $b = -9.67$ and $x_0 = 380.7$ (Model development, in bold). The T_b established in 2011 was 0.0 °C, in 2010 this same value was first considered for T_b and b parameter was maintained (Application of the model), but then it was established at 2.6 °C while the b parameter was calibrated to -5.11 (Calibration and validation). These new parameters were back applied to the data of 2011 to ensure that the model was still accurate (Back results with calibrated values).

Depth	Model	Application	Calibration and	Back results with
	development	of the model	validation	calibrated values
	2011	2010	2010	2011
	$T_b = 0.0\text{ }^{\circ}\text{C};$ $b = -9.67$	$T_b = 0.0\text{ }^{\circ}\text{C};$ $b = -9.67$	$T_b = 2.6\text{ }^{\circ}\text{C};$ $b = -5.11$	$T_b = 2.6\text{ }^{\circ}\text{C};$ $b = -5.11$
0 cm	10.1	24.2	7.3	13.5
2 cm	10.3	30.3	18.6	7.5
4 cm	8.9	19.6	12.6	11.4
6 cm	3.9	28.5	18.4	9.7
8 cm	7.8	17.8	16.1	13.7
Average	8.2	24.1	14.6	11.2

tion of *A. retroflexus*, although Guo & Al-Khatib (2003) denote a decline in the germination of this species at 35/30 °C day/night rhythms. This might suggest that different populations could have adapted to contrasting environmental conditions, and that threshold temperature values could be different for those populations, as suggested by Royo-Esnaol et al (2022) for *Echinochloa* populations. On the other hand, alternating temperatures have been reported as effective stimulants for the seed germination of *Amaranthus* species (Guo & Al-Khatib, 2003). Therefore, high temperatures during summer may have prevented seeds from germinating probably by induction of dormancy when it is too late and when the life cycle probably would not be completed. Despite this, Baskin & Baskin (1977) point out that *A. retroflexus* seeds do not enter secondary dormancy and thus, their ability to germinate during the summer remains.

Total seedling emergence was lower in 2010 than in 2011. This could be due to the differences in their level of dormancy. Freshly harvested seeds were used in 2010

while the same seeds stored at 5 °C for a year were used in 2011. The germination is known to increase after stratification at 4 °C in *Amaranthus tuberculatus* (León & Owen, 2003). Similarly, seed dormancy in *A. retroflexus* can be released either by stratification or by autumn–winter burial condition (Kępczyński & Sznigir, 2013) and after-ripening during dry storage (Schonbeck & Egley, 1980). Moreover, emergence showed one main flush between 350 and 450 HTT with sporadic emergence over an extended period before and after the flush, which corresponded to middle/end of March and beginning of April in our conditions.

At first, a logical thought would suggest a delay of seedling emergence with deeper burial depths. But in the present work, seedling emergence was delayed in seeds placed at the soil surface both years, compared to buried ones. The greater temperature and moisture fluctuation at the soil surface, detrimental for successful germination and seedling survival, may have contributed to this result. Nonetheless, it is known that seeds placed near the soil surface are subjected to cyclic fluctuations in soil water content that may

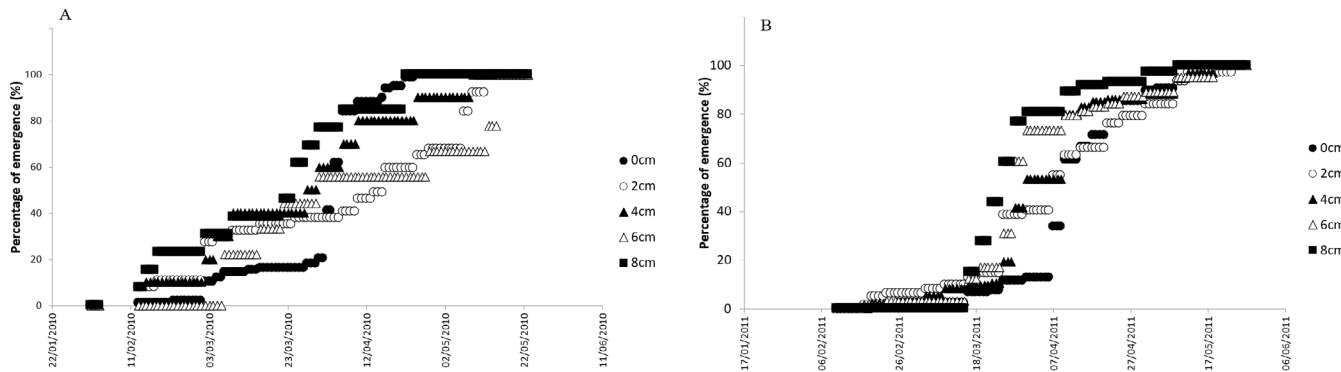


Figure 2. Cumulative emergence at each depth in 2010 (A) and in 2011 (B).

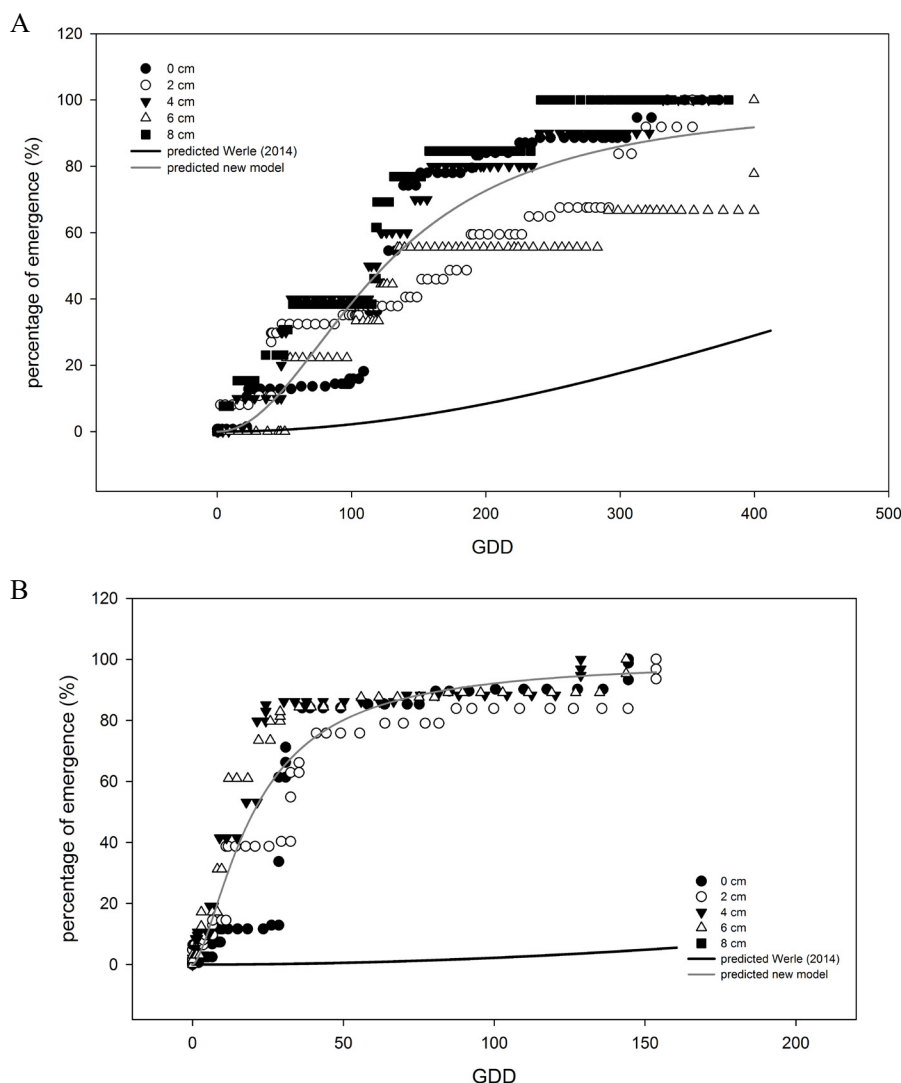


Figure 3. Cumulative emergence at every depth in 2010 (A) and 2011 (B) with a base temperature (T_b) of 9 °C. The black line represents the emergence model from Werle et al. (2014) considering this same T_b , and the grey line the new emergence model (logistic), also considering a T_b of 9 °C. GDD: growing degree days.

induce secondary dormancy (Downs & Cavers, 2000). In the case of *A. retroflexus*, continuous temperature fluctuation above and below the T_b value could delay the accumulated HTT and, hence, the emergence of the seedlings.

Despite the delay in the emergence timing, the total number of emerged seedlings was higher in seeds placed at the soil surface, which decreased with depth up to 8 cm in both years. Light abundance and temperature fluctuation are known to stimulate the germination of seeds (Taab & Andersson, 2009b). Hu et al. (2018) observed that the germination of some species, including *A. retroflexus*, was positively affected by light and moisture. Light usually favors small seed species, and can affect dormancy termination in the soil surface, as it happened in the present work when seeds were placed in the soil surface. However, at shallow depths (<2 cm) seeds can

be exposed to wet-dry cycles that could provoke either fatal germination (not reaching the soil surface) or induction to secondary dormancy (Benvenuti & Mazzoncin, 2018), less probable in *A. retroflexus*, according to Baskin & Baskin (1977). In either case, seedlings would not emerge, and this would explain the results obtained between 2 and 8 cm.

The results showed that the already developed models failed to predict the cumulative emergence pattern of the studied *A. retroflexus* population (Werle et al., 2014). However, the logistic emergence model showed potential to describe the emergence pattern (Figs. 3 A and B) that was well improved (RMSE < 15; Royo-Esnal et al., 2010) with new parametrization (Figs. 4 and 5). Therefore, a HTT based logistic function was found best to successfully model the seedling emergence pattern of the studied *A.*

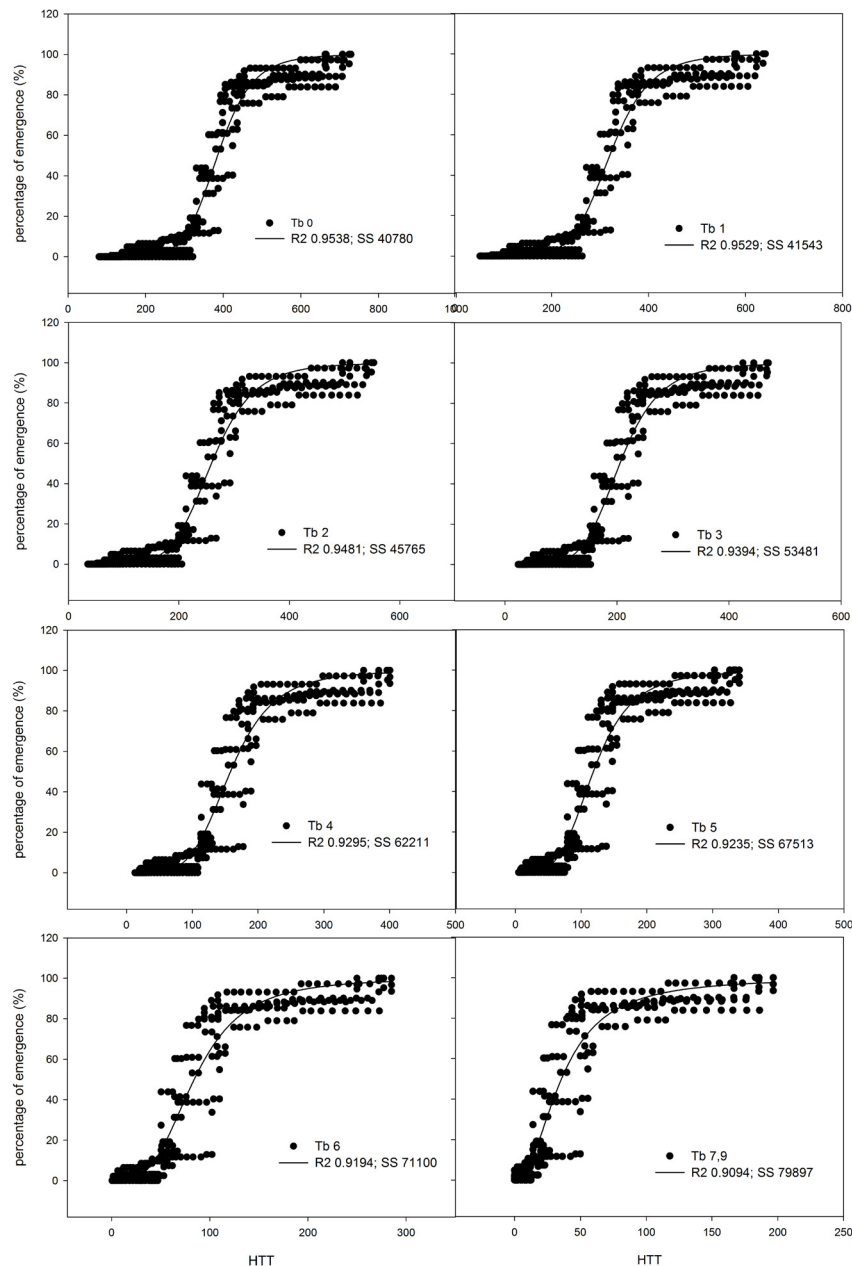


Figure 4. Hydrothermal time (HTT) based models developed for the emergence of *Amaranthus retroflexus* at different depths, from 0 to 8 cm in 2011, considering increasing T_b values: A, $T_b = 0$ °C; B, $T_b = 1$ °C; C, $T_b = 2$ °C; D, $T_b = 3$ °C; E, $T_b = 4$ °C; F, $T_b = 5$ °C; G, $T_b = 6$ °C; H, $T_b = 7.9$ °C. R^2 and sum of square (SS) values are provided for each model. Black points, observed emergence; black line, adjusted emergence model.

retroflexus population from west of Iran. Despite the good fit of the model, up to 40% of seedlings already emerged from 4 to 8 cm depth about 200 HTT before the model prediction. This great accumulation of HTT is explained by the low established T_b (2.6 °C). Emergence occurred during March, when temperatures at 0 cm, where cotyledons emerge, ranged between 5.2 °C and 18.4 °C, with a mean monthly temperature of 11.4 °C. According to Wang et al. (2022), the vigor index (VI) of *A. retroflexus* seedlings was lowest at a 10/20 °C regime (VI = 38-42) than at 15/25 °C

(VI = 1282-1369), and it was highest at 20/30 °C (3541-3857). Thus, it is expected those seedlings emerged by this period (March) to present a slow growth and remain small enough for a weed management actuation.

The estimated T_b for seedling emergence in 2011 (0 °C) was lower than that of 2010 (2.6 °C). This can be associated with the differences in dormancy level (Baskin & Baskin, 2014) between seeds used in both years, as it has been explained above. Different T_b requirements for emergence of *A. retroflexus* have been reported in various studies: 4

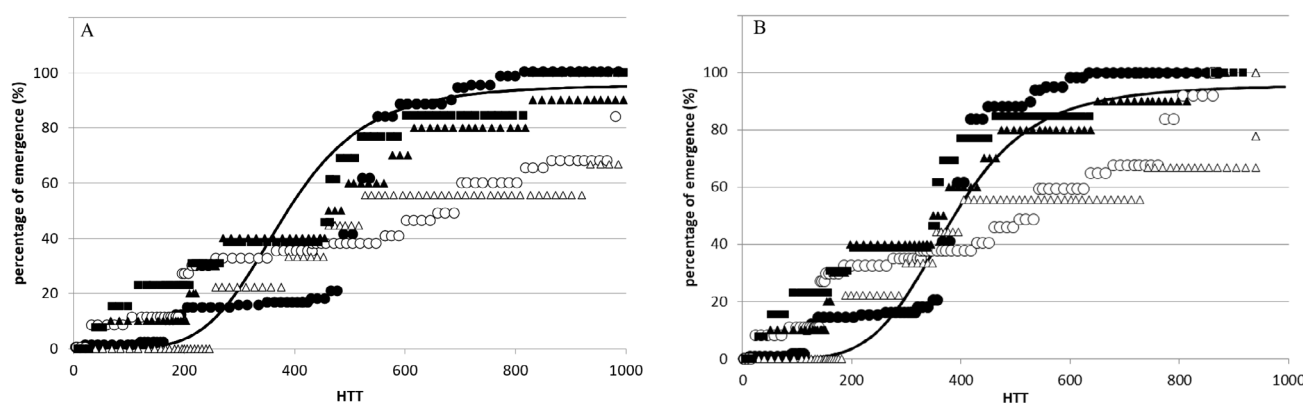


Figure 5. Calibration and validation of the emergence model developed with the data from 2011 against data from 2010 considering 0 °C as T_b and -9.67 the b value of the model (A), and its calibration using 2.6 °C as T_b and -5.11 the b value (B). Black line, adjusted emergence model.

°C for a French population (Gardarin et al., 2009), 8.9 °C in another French population (Guillemin et al., 2013), between 12.1 and 12.3 °C for Italian populations (Masin et al., 2010), at 9 °C in a North America population (Werle et al., 2014) and between 10 to 12.9 °C in populations from Gorgan, north of Iran (Loddo et al., 2018). This variation in the T_b suggests that models should be developed for similar agroclimatic areas, as suggested by Sousa-Ortega et al. (2020).

In summary, *Amaranthus retroflexus* is a weed species with potential to emerge over an extended period in the field. The number and pattern of its seedling emergences are likely to be associated with change in dormancy and it is also affected by soil depth. The logistic emergence model could successfully predict the seedling emergence of *A. retroflexus* considering dynamic T_b depending on the change in germination requirements due to different stratification/after-ripening level. Therefore, changes in T_b for emergence need to be taken into account when using the model to describe the seedling emergence of this species. Soil disturbance regimes might be applied to manage the seed pool of the species in the soil, as exposure to light and temperature fluctuations can enhance this species' emergence. These results contribute to optimize and improve the control measures for *A. retroflexus* in the cultivations.

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