



## Evaluation of a model for predicting *Avena fatua* and *Descurainia sophia* seed emergence in winter rapeseed

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### Abstract

*Avena fatua* and *Descurainia sophia* are two important annual weeds throughout winter rapeseed (*Brassica napus* L.) production systems in the semiarid region of Iran. Timely and more accurate control of both species may be developed if there is a better understanding of its emergence patterns. Non-linear regression techniques are usually unable to accurately predict field emergence under such environmental conditions. The objectives of this research were to evaluate the emergence patterns of *A. fatua* and *D. sophia* and determine if emergence could be predicted using cumulative soil thermal time in degree days (CTT). In the present work, cumulative seedling emergence from a winter rapeseed field during 3 years data set was fitted to cumulative soil CTT using Weibull and Gompertz functions. The Weibull model provided a better fit, based on coefficient of determination ( $R^2_{sqr}$ ), root mean square of error (RMSE) and Akaike index ( $AIC_d$ ), compared to the Gompertz model between 2013 and 2016 seasons for both species. Maximum emergence of *A. fatua* occurred 70-119 days after sowing or after equals 329-426 °Cd, while in *D. sophia* it occurred 119-134 days after sowing rapeseed equals 373-470 °Cd. Both models can aid in the future study of *A. fatua* and *D. sophia* emergence and assist growers and agricultural professionals with planning timely and more accurate *A. fatua* and *D. sophia* control.

**Additional key words:** *Brassica napus* L.; thermal time; Weibull; Gompertz

**Abbreviations used:**  $AIC_d$  (corrected Akaike's information); CTT (cumulative soil thermal time);  $R^2_{sqr}$  (adjusted coefficient of determination); RMSE (root mean square error); TT (thermal-time model); °Cd (soil thermal time).

**Authors' contributions:** Conceived and designed the experiments, analyzed the data and wrote the paper: MAA and SN. Performed the experiments, and contributed reagents/materials/analysis tools: SN. Critical revision of the manuscript for important intellectual content: JLGA.

**Topic:** Agricultural environment and ecology

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### Introduction

Wild oat (*Avena fatua*) and flixweed (*Descurainia sophia*) are noxious weed species distributed worldwide which produce severe yield and quality losses in cereal and oil seed crops in temperate and semiarid climates (Holm *et al.*, 1977; Blackshaw *et al.*, 1981). In the semiarid region of Iran, *A. fatua* and *D. sophia* are major weeds in winter cereals and rapeseed (*Brassica napus* L.) which their field emergence patterns show great year-to-year variability mainly due to the effect of highly unpredictable precipitation regimes as well as a complex seed bank dormancy behaviour regulated by both, genetic and environmental factors.

The timing and progression of seedling emergence are important determinants of weed competitiveness, susceptibility to control measures, and reproductive success (Blackshaw *et al.*, 1981; Forcella *et al.*, 2000). Early weed emergence relative to the crop allows weeds to compete better with crops. Many authors have reported that the magnitude of crop yield losses from crop-weed competition, among other factors, depends on the time of weed seedling emergence relative to that of the crop (Chikoye *et al.*, 1995; Knezevic *et al.*, 1997; Moechnig *et al.*, 2003). Hence, to control weeds adequately, especially with limited use of herbicides, farmers need to know the timing and extent of weed

seedling emergence before and during the growing season. Armed with such knowledge, farmers can better time the allocation of their resources and energies to actual weed problems, either through hand labour, work animals, and mechanized implements or through herbicides (Ekeleme *et al.*, 2005).

Field emergence predictive models are essential tools for the development of weed management support systems aimed to design sustainable weed control programs while optimizing crop yield. Such models should be able to minimize the degree of uncertainty on the estimation of the time and magnitude of seedling emergence (Forcella *et al.*, 2000). Various emergence models have been used to describe seed emergence, specifically, the thermal-time model (TT), which has been used extensively (Probert, 1992; Bradford, 2002; Royo-Esnaola *et al.*, 2010). In these models, average air or soil temperature above a specified threshold is accumulated over the days until weed emergence (Royo-Esnaola *et al.*, 2010).

Use of TT in emergence models became successful with the realization that emergence can be represented by a simple continuous cumulative sigmoidal curve, but only if the upper few centimeters of field soil remained continuously moist, either through irrigation or natural rainfall (Forcella *et al.*, 2000).

The objective of this study was to develop models of seedling emergence for *A. fatua* and *D. sophia* present in winter rapeseed crop and to examine whether TT is an appropriate variable for describing the timing of emergence of their seedlings.

## Material and methods

### Experimental sites and design

Field experiments were conducted between 2013 and 2016 in a winter rapeseed field at the experimental farm of Islamic Azad University, Karaj Branch, Iran. The site is located at latitude 35°45' N, longitude 51°6' E and 1313 meters above the sea level in semi-arid climate. The soil type was a silty clay (10.33% sand, 46.33% silt, 43.34% clay), with 0.98% organic matter and pH of 7.4.

Experimental site was under a continuous rapeseed-corn crop rotation for more than 10 years and had *A. fatua* and *D. sophia* infestations. To prepare the field, it was irrigated before conducting the experiment and after the field got wet enough, it was 30-cm depth mouldboard ploughed in a few days before sowing in August, followed by a disking to slice plant residue and incorporate fertilizers into the soil. Fertilizers were applied at 150:80:80 N:P:K kg/ha using urea (46%

N), diammonium phosphate (18% N, 46% P<sub>2</sub>O<sub>5</sub>) and potassium sulfate (50% K<sub>2</sub>O) as source of N, P and K, respectively during each experimental year. Full dose of P, K and 1/3 of N were applied before sowing and incorporated. Other portions of N were used at the end of rosette stage and beginning of the flowering. In the three years, rapeseed (cv. Okapi) was sown on October 17-20. Each experimental plot (6.5×2.3 m) included 6 planting rows with 6 m in length and 30 cm in width. Average crop density was 80 plants/m<sup>2</sup>. In each of the three years of research, irrigation was done at a rate of 3500 m<sup>3</sup>/ha at five rapeseed growth stages of emergence, shooting, flowering, pod setting and grain filling.

*D. sophia* and *A. fatua* emergence data were recorded from sowing to harvesting of rapeseed weekly from 20 randomly located one square meter quadrates. Seedlings after counting were removed from the soil with a minimum of soil disturbance. No herbicide was used in all three growing seasons for weed control in the experimental plots. Soil temperature was recorded every hour during the experiment with a data-logger placed at a depth of 5-cm under the soil surface (Sharma *et al.*, 1976; Yousefi *et al.*, 2014). Daily rainfalls were obtained from a meteorology station located 7 km away from the experimental field (Fig. 1).

### Model description

The cumulative soil thermal time (CTT) was estimated daily during the growing season with the following equation (Leblanc *et al.*, 2003; Leguizamón *et al.*, 2005; Izquierdo *et al.*, 2013):

$$CTT = \sum_{i=1}^n (T_{mean} - T_{base}) \quad [1]$$

where  $T_{mean}$  is the daily average soil temperature (°C),  $T_{base}$  is the lowest temperature for germination of *A. fatua* and *D. sophia* and  $n$  is the number of days after sowing.  $T_{base}$  was 1 °C for *A. fatua* (Cousens *et al.*, 1992) and 2.5 °C for *D. sophia* (Kiemnce & Mcinnis, 2002). This method is accurate if the minimum temperature is above the base temperature. However, if the minimum temperature decreases below the base temperature, negative values are obtained. When the minimum temperature <  $T_{base}$  no thermal time was assumed to accumulate (Leguizamón *et al.*, 2005).

Two different functions were tested for describing the time trend of weed seedling emergence, Weibull (Eq. [2]) and Gompertz (Eq. [3]):

$$Y = 100 * \left( 1 - e^{(-b(CTT-z)^c)} \right) \quad [2]$$

$$Y = 100 * e^{\left(-e^{-(b(CIT-m))}\right)} \quad [3]$$

$$AIC_d = \log(RMSE^2) + \frac{2m^d}{N} \quad [4]$$

where  $Y$  represents the cumulative percentage of emergence,  $b$  is the rate of increase of emergence once it is initiated,  $z$  is the time of first emergence and  $c$  is a parameter determining the shape of the curve and  $m$  represents the point of inflection on the  $x$  axis. Weibull and Gompertz distributions have been used commonly in the development of weed emergence models (Izquierdo *et al.*, 2013; Royo-Esnal *et al.*, 2015). Model parameters of both species were estimated with SigmaPlot 12.0 using a non-linear regression fitting routine.

### Models analysis

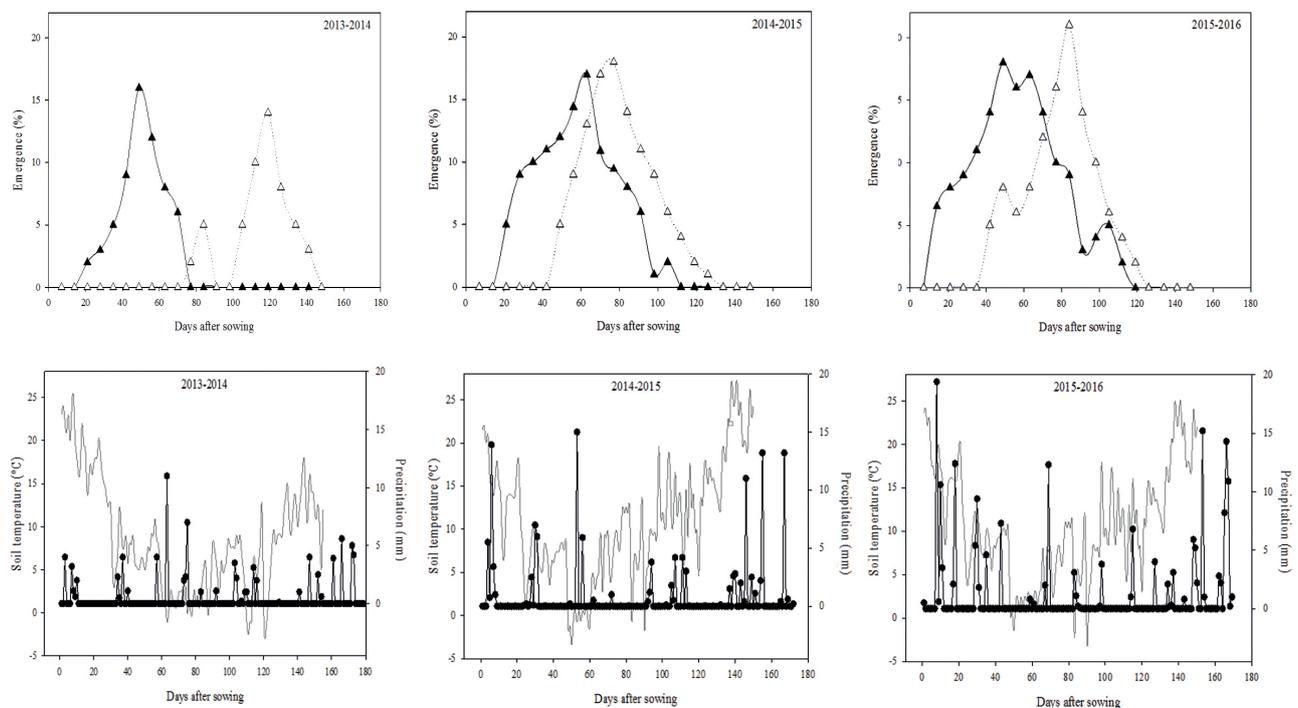
In all cases, goodness-of-fit measures were based on means of the adjusted coefficient of determination ( $R^2_{sq}$ ), root mean square error (RMSE) and the corrected Akaike's information ( $AIC_d$ ).

The general definition of  $AIC_d$  provided in Qi & Zhang (2001) was adopted (Eq. [4]), where  $m$  is the number of parameters of the model,  $N$  is the number of observations and  $d$  is a user defined constant, which allows the tuning of the penalty term.

### Results

In Fig. 1, emergence patterns of *A. fatua* and *D. sophia* are shown. *A. fatua* seedling emergence in 2014/15 started 21 days after sowing and showed a marked flush followed by a short flush (63 and 105 days after sowing, respectively). *A. fatua* emergence in 2015/16 started earlier, 14 days after sowing, and showed two marked flushes (49-63 days after sowing) and a short one (98 days after sowing). In 2013/14, only one big flush of emergence was observed. In 2014/15 and 2015/16 mean emergence was 116 seedlings/m<sup>2</sup> and 146 seedlings/m<sup>2</sup>, respectively, while in 2013/14 mean emergence was reduced to 61 seedlings/m<sup>2</sup>.

*D. sophia* emergence during 2014/15 season started 49 days after sowing and showed one marked flush 77 days after sowing (Fig. 1). Emergence in 2015/16 also started 42 days after sowing and showed a short (49 days after sowing) and a marked (84 days after sowing) flushes. In 2013/14, emergence was not reported until 78 days after sowing. In 2013/14, 2014/15 and 2015/16



**Figure 1.** Relative distribution (%) of *Avena fatua* (▲) and *Descurainia sophia* (Δ) seedling emergence during three consecutive seasons (upper graphs); daily mean soil temperatures (solid line) at 5 cm depth and daily total precipitation (●) during the experimental years (lower graphs).

**Table 1.** Comparison between thermal-emergence model outputs (Weibull and Gompertz) obtained after data fitting for *Avena fatua* and *Descurainia sophia*.

Function	Species	Season	$R^2_{sqr}$ [1]	RMSE [2]	AIC <sub>d</sub> [3]
Weibull	<i>A. fatua</i>	2013/14	0.9735	4.61	132.18
		2014/15	0.9891	3.13	115.98
		2015/16	0.9914	3.14	116.13
	<i>D. sophia</i>	2013/14	0.9871	2.65	109.06
		2014/15	0.9925	3.19	116.77
		2015/16	0.9934	3.11	115.6
Gompertz	<i>A. fatua</i>	2013/14	0.9293	7.31	149.51
		2014/15	0.9863	3.51	118.79
		2015/16	0.9853	4.11	125.43
	<i>D. sophia</i>	2013/14	0.9847	3.96	110.71
		2014/15	0.9912	3.46	118.16
		2015/16	0.9911	3.13	119.87

[1]  $R^2_{sqr}$ : adjusted coefficient of determination. [2] RMSE: root mean squares error. [3] AIC<sub>d</sub>: corrected Akaike's information.

mean emergence was 52, 109 and 112 seedlings/m<sup>2</sup>, respectively.

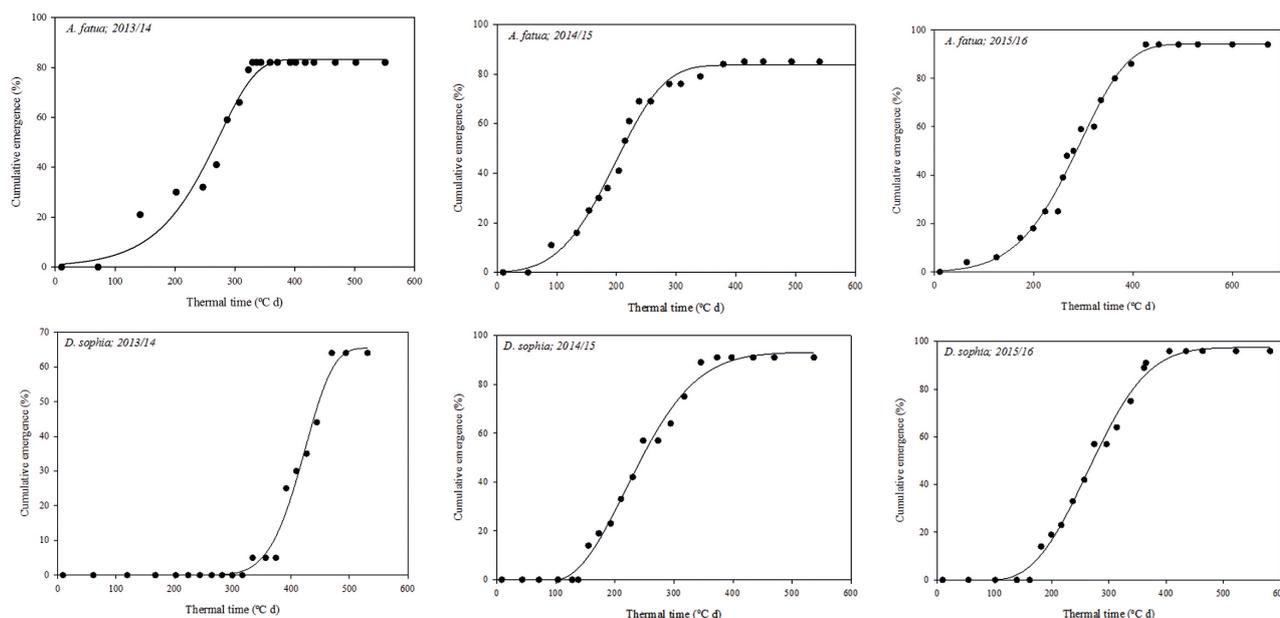
The Weibull model provided a better fit, based on  $R^2_{sqr}$ , RMSE and AIC<sub>d</sub>, compared to the Gompertz model between 2013 and 2016 seasons for both species (Table 1).

According to the CTT model, *A. fatua* emergence started at 142 and 91 °Cd (soil thermal time) of the season in 2013/14 and 2014/15, respectively, while in 2015/16 emergence started at 65 °Cd. Afterwards, seedling emergence increased steadily and reached 50 and 90% of total emergence at 269 and 316 °Cd, respectively in 2013/14, at 205 and 313 °Cd, respectively in 2014/2015,

and at 296 and 389 °Cd, respectively in 2015/2016 (Fig. 2). *D. sophia* started emergence at 316, 155 and 181 °Cd in 2013/14, 2014/15 and 2015/16, respectively, and reached 50 and 90% of total emergence at 234 and 331 °Cd in 2014/15, respectively, and at 263 and 357 °Cd in 2015/16, respectively, while in 2013/14 reached only 50% by 416 °Cd (Fig. 2).

## Discussion

We used the 2013 to 2016 data to select a model that generally produced the lowest RMSE and AIC<sub>d</sub>



**Figure 2.** *Avena fatua* (upper graphs) and *Descurainia sophia* (lower graphs) cumulative seedling emergence as predicted by cumulative soil thermal time (CTT) during three consecutive seasons in Iranian rapeseed. Observed (symbols) and predicted (lines) emergence data according to a Weibull function.

and also higher  $R^2_{sqr}$  for cumulative TT at the target emergence stage (Table 1). In the semiarid region of Iran, *A. fatua* and *D. sophia* show an irregular seedling emergence behaviour along the season and a great variability among years mainly due to a highly unpredictable precipitation regime, also influenced by a fluctuating thermal environment and seed dormancy level variations within the population.

According to these results, Weibull function was chosen to describe *A. fatua* and *D. sophia* emergence related to thermal and corrected TT. Our results partially agree with Yousefi *et al.* (2013) in a comparison of three models (Gompertz, Logistic and Weibull models) on *D. sophia*, who found that the Weibull model gave the best fit for Iran climate. Chantre *et al.* (2012) reported that the Weibull model was deemed to provide a better fit than the other models for *A. fatua* seedling emergence in Argentina. However, Gonzalez-Diaz *et al.* (2007) reported that the Logistic model was deemed to provide a better fit than the other models for *A. fatua* seedling emergence in Spain. The differences between *A. fatua* and *D. sophia* emergence patterns in semiarid conditions might be attributed mainly to a highly unpredictable precipitation regime, fluctuating thermal environment and seed dormancy level variations (Chantre *et al.*, 2012). In addition to weather conditions, different soil management (such as cultivation operation and working depth) may affect the accuracy of the model by varying the vertical movement of the seeds within the soil profile (Grundy, 2003).

In all years, maximum emergence of *A. fatua* was reached 70-119 days after sowing or after 329-426 °Cd had accumulated (Fig. 2). From the farmer's point of view, seedlings that emerge at the onset of the rainy season, in autumn, are of minor importance, as they are suppressed by cultivation during seedbed preparation for sowing. However, this cultivation stimulates germination and new seedlings emerge simultaneously with the crop (Izquierdo *et al.*, 2013). A wide range of days for maximum wild oat emergence have been reported. For example, Yousefi *et al.* (2014) in Iran found that 100% emergence of *A. fatua* was reached 84 days (>500 °Cd) after sowing date. Martinson *et al.* (2007) in USA indicated that 100% emergence of *A. fatua* was reached 28 to 42 days (400-600 °Cd) after initial emergence. The differences in reported time to maximum emergence are most likely because of weather conditions and possibly dormancy. Sharma *et al.* (1976) found that maximum emergence of wild oat was reached 17 days after seeding and no further emergence occurred 30 days after seeding in USA. Non dormant *A. fatua* seeds may undergo secondary dormancy if the conditions for their germination

are unfavourable. *A. fatua* prefers cool climate and moist soil conditions (Sharma & Vanden Born, 1978; Yousefi *et al.*, 2014). Our experimental site presents warmer and drier conditions than USA, which could affect secondary dormancy, leading to an extended emergence period. Imam & Allard (1965) observed genetic variability within wild oat populations in the same region as well as across regions. Such species variability is another potential explanation for the emergence range in reported temperatures. Mickelson & Grey (2006) found that wild oat seed mortality increased linearly as soil water content increased. In our study, *A. fatua* emergence in 2015/16 showed an earlier starting than 2013/14 and 2014/15 seasons. Later onsets in field emergence of *A. fatua* in 2013/14 and 2014/15 were also markedly influenced by rainfall and soil temperatures. Wild oat tends to prefer cool, moist soil conditions for emergence (Sharma & Vanden Born, 1978). Sexsmith (1969) determined that temperature had a greater effect than soil moisture on wild oat seed dormancy. In this three years study just prior to wild oat emergence, soil temperatures were higher than 20 °C (Fig. 1). Therefore, soil moisture is an important factor in the wild oat emergence in semiarid conditions. In our experiments, the beginning of the 2013/14 season was drier than the previous seasons; rainfall during 60 days after sowing winter rapeseed in 2013/14, 2014/15 and 2015/16 was 34, 40 and 73 mm, respectively (Fig. 1). Patterns of emergence in relation to rainfall, cultivation and tillage system are different because of climate and management variability (Ogg & Dawson, 1984; Cardina & Hook, 1989). Results showed that maximum emergence of *D. sophia* was reached 119-134 (late autumn) days after sowing or after 373-470 °Cd (Fig. 2). Best (1977) reported that seeds of *D. sophia* germinated most readily in late autumn and early spring, while germination was rare during summer. *D. sophia* emergence during 2014/15 and 2015/16 was earlier than 2013/14 season. Important rainfall events with high soil temperatures in the autumn occurred at the beginning of emergence in 2014/15 and 2015/16 seasons, which probably promoted early emergence (Fig. 1). Maybe the dormancy release rate was increased by hydration events in the soil (Gallagher *et al.*, 2004). In 2013/14, soil temperature was lower before emergence compared to 2014/15 and 2015/16. In winter annuals like *D. sophia*, although emergence of seeds is inhibited under water stress conditions, no secondary dormancy appears to develop if temperature and light conditions are adequate. In the case of winter annuals, high autumn temperatures promote the full loss of dormancy and increased emergence, while low winter temperatures may, wholly or partially

depending on the species, prevent loss of dormancy (Baskin & Baskin, 1989).

In summary, the main topic of this study was to develop an explicit predictive model of emergence for *A. fatua* and *D. sophia* seedlings in the semiarid region of Iran using meteorological data easily available to farmers and practitioners. Having the ability to accurately predict the emergence for both species in rapeseed has practical implications on post-emergence herbicide application timing and efficacy. Many growers would prefer to time the control operations in their fields as soon as 100% of the emergence for both species population occurs. However, validation of such a predictive model for *A. fatua* and *D. sophia* would require repeating the germination phenology study in different years and perhaps in different locations.

## References

- Baskin JM, Baskin CC, 1989. Germination responses of buried seeds of *Capsella bursa-pastoris* exposed to seasonal temperature changes. *Weed Res* 29: 205-212. <https://doi.org/10.1111/j.1365-3180.1989.tb00860.x>
- Best KF, 1977. The biology of Canadian weeds. *Descurainia sophia* (L.) Webb. *Can J Plant Sci* 57: 499-507. <https://doi.org/10.4141/cjps77-073>
- Blackshaw RE, Stobbe EH, Sturko ARW, 1981. Effect of seeding dates and densities of green foxtail (*Setaria viridis*) on the growth and productivity of spring wheat (*Triticum aestivum*). *Weed Sci* 29: 212-217.
- Bradford KJ, 2002. Applications of hydrothermal time to quantifying and modeling seed germination and dormancy. *Weed Sci* 50: 248-260. [https://doi.org/10.1614/0043-1745\(2002\)050\[0248:AOHTTQ\]2.0.CO;2](https://doi.org/10.1614/0043-1745(2002)050[0248:AOHTTQ]2.0.CO;2)
- Cardina J, Hook JE, 1989. Factors influencing germination and emergence of Florida beggarweed (*Desmodium tortuosum*). *Weed Technol* 3: 402-407.
- Chantre GR, Blanco AM, Lodovichi MV, Bandoni AJ, Sabbatini MR, Lopez R.L, Vigna MR, Gigon R, 2012. Modeling *Avena fatua* seedling emergence dynamics: An artificial neural network approach. *J Comput Electron* 88: 95-102. <https://doi.org/10.1016/j.compag.2012.07.005>
- Chikoye DS, Weise SF, Swanton CJ, 1995. Influence of common ragweed (*Ambrosia artemisiifolia*) time of emergence and density on white bean (*Phaseolus vulgaris*). *Weed Sci* 43: 375-380.
- Cousens R, Weaver SE, Porter JR, Rooney JM, Butler DR, Johnson MP, 1992. Growth and development of *Avena fatua* L. in the field. *Ann Appl Biol* 120: 339-351. <https://doi.org/10.1111/j.1744-7348.1992.tb03430.x>
- Ekeleme F, Forcella F, Archer DV, Akobundu IO, Chikoye D, 2005. Seedling emergence model for tropic ageratum (*Ageratum conyzoides*). *Weed Sci* 53: 55-61. <https://doi.org/10.1614/WS-03-147R1>
- Forcella F, Benech-Arnold RL, Sanchez R, Ghersa CM, 2000. Modeling of seedling emergence. *Field Crop Res* 67: 123-139. [https://doi.org/10.1016/S0378-4290\(00\)00088-5](https://doi.org/10.1016/S0378-4290(00)00088-5)
- Gallagher RS, Kathryn JS, Crawford AD, 2004. Alleviation of dormancy in annual ryegrass (*Lolium rigidum*) seeds by hydration and after-ripening. *Weed Sci* 52: 968-975. <https://doi.org/10.1614/WS-04-075R>
- Gonzalez-Diaz L, Leguizamon E, Forcella F, Gonzalez-Andujar JL, 2007. Short communication: Integration of emergence and population dynamic models for long term weed management using wild oat (*Avena fatua* L.) as an example. *Span J Agric Res* 5: 199-203. <https://doi.org/10.5424/sjar/2007052-245>
- Grundy AC, 2003. Predicting weed emergence: a review of approaches and future challenges. *Weed Res* 43: 1-11. <https://doi.org/10.1046/j.1365-3180.2003.00317.x>
- Holm LG, Plunknett DL, Pancho JV, Herberger JP, 1977. The world's worst weeds: distribution and biology. Hawaii Univ. Press; Honolulu, Hawaii, USA.
- Imam AG, Allard RW, 1965. Population studies in predominantly self-pollinated species. VI. Genetic variability between and within natural populations of wild oats from differing habitats in California. *Genetics* 51: 49-62.
- Izquierdo J, Bastida F, Lezaun JM, Sanchez del Arco MJ, Gonzalez-Andujar JL, 2013. Development and evaluation of a model for predicting *Lolium rigidum* emergence in winter cereal crops in the Mediterranean area. *Weed Res* 53: 1-10. <https://doi.org/10.1111/wre.12023>
- Kiemnce GL, Mcinnis ML, 2002. Hoary cress (*Cardaria draba*) root extract reduces germination and root growth of five plant species. *Weed Technol* 16: 231-234. [https://doi.org/10.1614/0890-037X\(2002\)016\[0231:HCCDRE\]2.0.CO;2](https://doi.org/10.1614/0890-037X(2002)016[0231:HCCDRE]2.0.CO;2)
- Knezevic SZ, Horak MJ, Vanderlip RL, 1997. Relative time of redroot pigweed (*Amaranthus retroflexus* L.) emergence is critical in pigweed-sorghum [*Sorghum bicolor* (L.) Moench] competition. *Weed Sci* 45: 502-508.
- Leblanc ML, Cloutier DC, Stewart K, Hamel C, 2003. The use of thermal time to model common lambsquarters (*Chenopodium album*) seedling emergence in corn. *Weed Sci* 51: 718-724. <https://doi.org/10.1614/P2002-108>
- Leguizamon ES, Fernandez QC, Barroso J, Gonzalez-Andujar JL, 2005. Using thermal and hydrothermal time to model seedling emergence of *Avena sterilis* ssp. *ludoviciana* in Spain. *Weed Res* 45: 149-156. <https://doi.org/10.1111/j.1365-3180.2004.00444.x>
- Martinson K, Durgan B, Forcella F, Wiersma J, Spokas K, Archer D, 2007. An emergence model for wild oat (*Avena fatua*). *Weed Res* 55: 584-591. <https://doi.org/10.1614/WS-07-059.1>
- Mickelson JA, Grey WE, 2006. Effect of soil water content on wild oat (*Avena fatua*) seed mortality and seedling

- emergence. *Weed Sci* 54: 255-262. <https://doi.org/10.1614/WS-05-007R.1>
- Moechnig MJ, Stoltenberg DE, Boerboom CM, Binning LK, 2003. Empirical corn yield loss estimation from common lambsquarters (*Chenopodium album*) and giant foxtail (*Setaria faberi*) in mixed communities. *Weed Sci* 51: 386-393. [https://doi.org/10.1614/0043-1745\(2003\)051\[0386:ECYLEF\]2.0.CO;2](https://doi.org/10.1614/0043-1745(2003)051[0386:ECYLEF]2.0.CO;2)
- Ogg AG, Dawson JH, 1984. Time of emergence of eight weed species. *Weed Sci* 32: 327-335.
- Probert RJ (ed), 1992. The role of temperature in germination ecophysiology. In: *Seeds: The ecology of regeneration in plant communities*; Fenner M (ed), pp: 285-325. CABI Publ., Wallingford, UK.
- Qi M, Zhang GP, 2001. An investigation of model selection criteria for neural network time series forecasting. *Eur J Oper Res* 132: 666-680. [https://doi.org/10.1016/S0377-2217\(00\)00171-5](https://doi.org/10.1016/S0377-2217(00)00171-5)
- Royo-Esnal A, Torra J, Conesa JA, Forcella F, Recasens J, 2010. Modeling the emergence of three arable bedstraw (*Galium*) species. *Weed Sci* 58: 10-15. <https://doi.org/10.1614/WS-09-063.1>
- Royo-Esnal A, Necajeva J, Torra J, Recasens J, Gesch RW, 2015. Emergence of field pennycress (*Thlaspi arvense* L.): Comparison of two accessions and modelling. *Ind Crops Prod.* 66:161-169. <https://doi.org/10.1016/j.indcrop.2014.12.010>
- Sexsmith JJ, 1969. Dormancy of wild oat seed produced under various temperature and moisture conditions. *Weed Sci* 17: 405-407.
- Sharma MP, McBeath DK, Vanden Born, WH, 1976. Studies of the biology of wild oat. I. Dormancy, germination and emergence. *Can J Plant Sci* 56: 611-618. <https://doi.org/10.4141/cjps76-097>
- Sharma MP, Vanden Born WH, 1978. The biology of Canadian weeds. 27. *Avena fatua* L. *Can J Plant Sci* 58: 141-157. <https://doi.org/10.4141/cjps78-022>
- Yousefi AR, Rastgoo M, Ghanbari Motlagh M, Ebrahimi M, 2013. Predicting seedling emergence of flixweed (*Descurainia sophia* (L.) Webb.) and Hoary cress (*Cardaria draba* (L.) Desv.) in rapeseed (*Brassica napus*) field in Zanzan conditions. *J Plant Protec* 27: 48-54. [In Persian with English abstract].
- Yousefi AR, Oveisi M, Gonzalez-Andujar, JL, 2014. Prediction of annual weed seed emergence in garlic (*Allium sativum* L.) using soil thermal time. *Sci Hortic* 168:189-192. <https://doi.org/10.1016/j.scienta.2014.01.035>