

Germination, emergence modeling, longevity, and persistence in the hairy beggarticks seed bank

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Abstract: Background: Hairy beggarticks (*Bidens pilosa* L.) is a highly adaptable weed species that thrives in diverse environmental conditions. Understanding the environmental factors that influence its germination is essential for developing predictive emergence models and supporting integrated management strategies. **Objective:** The present study aimed to estimate the cardinal temperatures and water potentials for *B. pilosa* germination, assess seed bank longevity, and develop a field-based emergence model. **Methods:** Laboratory experiments were conducted to determine base temperature and water potential thresholds for seed germination. Eight temperatures (10, 15, 20, 25, 30, 35, 40, and 45 °C) and 10 water potentials (0, -0.05, -0.1, -0.2, -0.4, -0.6, -0.9, -1.2, -1.5, and -2.0 MPa) were tested. Field experiments were conducted from 2014 to

2018, with seedling emergence monitored under three sowing conditions. To assess seed bank longevity and persistence, a factorial experiment was set up using three burial depths (0, 3, and 6 cm) and five seed retrieval times (0, 1, 4, 10, and 16 months). **Results:** The base, optimal, and maximum temperatures for seedling emergence were 10.4, 24.7, and 41.9 °C, respectively. The base water potential was -0.85 MPa. Thermal and hydrothermal models were adequate to predict the emergence of hairy beggarticks at different soybean sowing dates. The species forms a transient seed bank; however, the greater burial depth was associated with increased seed longevity (16 months) in the soil. **Conclusions:** The models are able to predict emergence under the evaluated conditions, and deeper seed burial was associated with longer seed bank longevity.

Keywords: Biological parameters; Temperature; Water potential; *Bidens pilosa*.

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1. Introduction

Hairy beggarticks (*Bidens pilosa* L.) is an herbaceous, annual (and occasionally biennial) dicotyledonous species with a C3 photosynthetic pathway. It is sexually propagated and belongs to the family Asteraceae (Rojas-Sandoval, 2018). Native to tropical regions, including South America, *B. pilosa* has invaded various parts of the world and has become a problematic weed in several crops, such as soybean, sugarcane, beans, and corn (Stohlgren et al., 2013). To date, five cases of herbicide resistance have been reported worldwide, including three in Brazil, which have complicated its management. The first documented case occurred in 1993 and involved resistance to acetolactate synthase (ALS) inhibitors. In 2016, multiple resistance to both ALS and photosystem II (PSII) inhibitors was reported (López-Overejo et al., 2006; Takano et al., 2016). The most recent case, recorded in 2022, involved resistance to protoporphyrin oxidase (PPO) inhibitors in soybean crops (Heap, 2025).

Hairy beggarticks present a capitulum composed of 30 to 40 flowers. The achenes possess an aristate pappus that gives rise to two to three bristles, with trichomes oriented toward the base (Santos, Cury, 2011). These characteristics play a key role in the species' epizoochorous dispersal and its establishment in the field from seeds. The plants can flower multiple times during the growing season, producing seeds that contribute to the seed bank (Gurvich et al., 2004). A single hairy beggarticks plant can produce approximately 30,000 seeds (Rojas-Sandoval, 2018).

Seed germination rates are higher when exposed to alternating day and night temperatures around 25/15 °C and 30/20 °C (Chauhan et al., 2019). In contrast, germination decreases under dark conditions (Chauhan et al., 2019), as does seedling emergence when seeds are buried deeper than 2 cm (Souza et al., 2009). Dormancy has been observed in hairy beggarticks seeds presenting achenes with warty teguments, which are overcome upon exposure to light (Amaral, Takai, 1998). Germination and successful field establishment of *B. pilosa* require certain temperature and soil moisture thresholds. Therefore, predictive methods based on these conditions can help develop management practices that maximize control efficacy (Travlos et al., 2020).

Identifying base temperatures and water potential for seed germination is necessary to develop models capable of predicting emergence at different times of the year (Werle et al., 2014; Royo-Esnal et al., 2015). Empirical models have been used

to predict weed emergence based on thermal time (TT) (Izquierdo et al., 2013; Werle et al., 2014) or hydrothermal time (HT) (García et al., 2013; Masin et al., 2014; Royo-Esnal et al., 2015). These models are developed based on environmental conditions, allowing their application to predict weed emergence across different years and geographic regions (Werle et al., 2014). Knowledge about plant emergence timing enables the adaptation of management practices (Zandoná et al., 2018a), promoting more precise use of herbicides and integrated weed management (IWM) practices.

To improve the effectiveness of IWM, practices focused on weed seeds and seed bank dynamics should be considered, such as crop rotations, soil tillage, and harvest weed seed control (Haring, Flessner, 2018). Some of these practices aim to limit weed seed rain and dispersal while increasing seed loss in the soil. Understanding seed persistence in the weed seed bank helps determine species survival capacity and persistence under different conditions, contributing to informed decision-making and management (Schwartz-Lazaro, Copes, 2019). In this context, the present study aimed to (1) estimate the temperature and water potential parameters for hairy beggarticks germination, (2) assess the seed bank persistence of hairy beggarticks, and (3) develop a thermal and hydrothermal model to predict the field emergence of this species.

2. Materials and Methods

The experiments were conducted following the general methodology described by Zandoná et al. (2024). However, due to species-specific differences, certain procedures were modified. These variations are detailed in the subsections below.

2.1 Experimental conditions and location

Experiments to determine cardinal temperatures and water potential were carried out in growth chambers under a controlled photoperiod of 8/16 hours (light/dark). Each chamber was equipped with six 40-watt fluorescent lamps. The remaining experiments (related to modeling the emergence, longevity, and persistence of the *B. pilosa* seed bank) were conducted under field conditions between 2014 and 2018.

The experimental area was located in Capão do Leão, Rio Grande do Sul (RS), Brazil (31.80° S; 52.50° W), referred to as CAP. The soil at this site is classified as *Argissolo Vermelho-Amarelo*, with a sandy loam texture, and belongs to the Pelotas mapping unit (Santos, 2018). Validation of the emergence data was conducted in Cruz Alta, RS (28.60° S; 53.67° W), where the soil is classified as *Latossolo Vermelho distrófico* (Santos, 2018). Both regions have a humid subtropical climate (Cfa), characterized by humid temperate conditions, hot summers, and the absence of a well-defined dry season.

2.2 Seed collection and origin

For the temperature, water potential, and seed bank longevity experiments, hairy beggarticks seeds were collected between March and April 2016 from plants bearing mature terminal capitula. Collections were made from different populations located in CAP, *Cooperativa Central Gaúcha* (CCGL), and Barra Funda (27.93° S; 59.04° W). To ensure a representative sample, seeds from all locations were mixed prior to use in the experiments. Seed quality was then assessed through germination, viability, and dormancy tests. Viability was determined using the tetrazolium test (Ministério da Agricultura e Pecuária, 2009). In the emergence modeling experiments, seedlings emerged directly from the seed bank, without prior sowing of hairy beggarticks seeds.

2.3 Cardinal temperatures and base water potential

Three experiments were conducted using a completely randomized design, with four replicates of 50 seeds each. Two experiments aimed to determine the cardinal temperatures for germination, while the third focused on estimating the base water potential (Ψ_b). In the first and second experiments, seeds were exposed to eight constant temperatures: 10, 15, 20, 25, 30, 35, 40, and 45 °C. Based on the findings, the third experiment was carried out at 24.7 °C to determine the Ψ_b . The treatments included 10 water potential levels: 0, -0.05, -0.1, -0.2, -0.4, -0.6, -0.9, -1.2, -1.5, and -2.0 MPa. These conditions were simulated using different concentrations of polyethylene glycol 8000 (PEG).

Seeds were placed on blotting paper previously moistened with either distilled water (for the temperature experiments) or PEG solution (for the water potential experiment). The volume of water or PEG solution applied was equivalent to 2.5 times the dry mass of paper. The samples were then placed in acrylic boxes measuring 11 x 11 x 3.5 cm (Ministério da Agricultura e Pecuária, 2009). Germination was monitored daily. Germinated seeds were counted and removed to allow an accurate estimation of cumulative germination. A seed was considered germinated when the radicle reached at least 2 mm in length. Experiments were concluded when no additional germination was recorded for five consecutive days.

2.4 Emergence modeling

Field experiments were conducted over five years (2014–2018). Each year, three simulated sowing dates were established: October 20 (first), November 10 (second), and December 1 (third). Prior to these dates, the area was managed by sowing oats at a seed density of 80 kg ha⁻¹, with no soil disturbance. To prevent the emergence of hairy beggarticks and other weeds before the monitoring began, burndown applications of glyphosate (1440 g a.e. ha⁻¹) and

paraquat (300 g a.i. ha⁻¹) were performed 15 days and on the day (0) of each simulated soybean sowing date, respectively.

A total of 1,416.38 hairy beggarticks seeds m⁻² were found in the soil seed bank (0–5 cm depth). Emergence from the seed bank was monitored at four-day intervals for 24 days after the simulated sowing date, with an additional count of 48 days for each period (October 20, November 10, and December 1) across all years. This final assessment coincided with the complete interference prevention period for the soybean crop (Zandoná et al., 2018a). The experimental area was structured into four blocks, each containing four replicates. Plots measured 15.75 m² (3.15 x 5 m) per period (October, November, and December). Within each plot, four subplots were monitored, and all emerged weeds within a 0.25 m² area were counted. A plant was considered emerged when its aerial portion reached at least 1 cm above the soil surface.

Throughout the experiment, soil and ambient temperatures were recorded daily using a data logger (model HOBO® Pro v2 2x External Temperature). Soil moisture at a depth of 0–5 cm was measured every four days, coinciding with emergence monitoring (Goulart et al., 2020). Soil samples were collected using a sampling spear, weighed fresh, oven-dried, and reweighed to determine moisture content by calculating the difference between fresh and dry weights. Soil moisture percentages were then converted to soil water potential using the average soil water retention equation proposed by Bortoluzzi et al. (2008) for no-tillage systems.

2.5 Longevity and persistence of the seed bank

The experiment was conducted between July 2017 and November 2018. A total of 125 seeds were placed in 50 g of *Argissolo* soil and enclosed in nylon mesh bags (10 x 10 cm), which served as the experimental units. The number of seeds was chosen to ensure the presence of 50 viable seeds per sample. The experiment followed a 3 x 5 factorial arrangement in a randomized block design with four replicates. Factor A consisted of three seed burial depths (0, 3, and 6 cm), while factor B comprised five retrieval times (0, 1, 4, 10, and 16 months post-burial) (Vargas et al., 2018). For the 0 cm burial depth, the experimental units were positioned directly on the soil surface. The experimental area was planted with soybeans during the summer and left fallow in the winter.

At each retrieval time, seeds were removed from the bags and cleaned using a sprayer and a set of sieves with mesh sizes of 16, 32, and 60 (Vargas et al., 2018). The cleaned samples were then placed on filter paper to dry for 24 hours before being examined under a stereomicroscope to extract the remaining seeds (Vargas et al., 2018). These seeds underwent a germination test to assess physiological quality, following the methodology outlined by Ministério da Agricultura e Pecuária (2009). Non-germinated seeds were further subjected to the tetrazolium test (Ministério

da Agricultura e Pecuária, 2009) to determine viability, using 1.0% 2,3,5-triphenyl tetrazolium chloride; seeds were considered viable if they exhibited pink or carmine staining. Dormant seeds were those that remained viable but did not germinate, while non-viable seeds were classified as dead. Seeds that could not be recovered were presumed to have been predated, decayed, or lost due to germination.

The variables analyzed included the proportion of remaining, germinated, dead, and dormant seeds, with all results expressed as percentages (Ministério da Agricultura e Pecuária, 2009). The percentage of remaining seeds was calculated based on the initial seed count per replicate, whereas the percentages of germinated, dead, and dormant seeds were determined relative to the number of remaining seeds. Seed persistence was assessed by subtracting the sum of seeds that germinated in the laboratory and those classified as viable seeds in the tetrazolium test from the original seed count per replicate; the results were expressed as percentages.

2.6 Statistical analysis

In all experiments, data were tested for normality using the Shapiro–Wilk test and for homoscedasticity using the Hartley test prior to analysis of variance (ANOVA) at a significance level of $\alpha \leq 0.05$. When significant differences were detected, regression analysis was performed using SigmaPlot 14 (Systat Software, Inc., 2018).

For the temperature and water potential experiments, cumulative germination data were analyzed. The data were fitted to the Weibull logistic function (Equation 1) to estimate the time required to reach 50% germination (T_{50}) for each treatment (Dumur et al., 1990; Forcella et al., 2000; Goulart et al., 2020).

$$y = a [1 - e^{-(x-T_{50} + \frac{\ln 2}{b} c)}] \quad (1)$$

where: y is the germination percentage; x is the time (in days, TT or HT); a is the maximum emergence percentage; b is the rate of increase; c is a shape parameter; and T_{50} is the time (in days, TT or HT) required to achieve 50% germination or emergence.

To estimate the base (T_b), optimal (T_o), and maximum (T_{max}) temperatures, the germination rate was determined at $1/T_{50}$, and two independent linear regressions (sub- and supraoptimal ranges) were fitted, following the methodology described by Dumur et al. (1990). Ψ_b was obtained by plotting $1/T_{50}$ against each water potential and identifying the x-intercept of the regression line (Schermer et al., 2017). Confidence intervals ($p > 0.95$) were estimated using the bootstrap statistical method to obtain the most accurate values for T_b , T_o , and T_{max} , prioritizing the criterion of lowest residual deviation (Loddo et al., 2017). These values were then used to calculate TT and HT under different field conditions of temperature and water potential.

For field emergence modeling, data were converted into cumulative seedling emergence to represent total emergence over time. Soil temperature and moisture data were used to calculate TT and HT. The relationship between cumulative emergence was described using the Weibull function (Equation 1). Model validation was performed using emergence data from the CCGL experimental station by comparing observed emergence values with model predictions. Model accuracy was assessed using mean squared error (MSE) (Roman et al., 2000) and the Akaike Information Criterion (AIC) (Qi, Zhang, 2001), with lower values indicating a better fit between predicted and observed emergence.

In the seed bank assessment, regression analysis was applied to the retrieval times. The variables remaining seeds, germination, dormancy, and persistence were modeled using a three-parameter decreasing exponential regression equation (Equation 2):

$$y = y_0 + a \cdot e^{(-b \cdot x)} \quad (2)$$

where: y is the response variable of interest; x represents the collection times; e is the exponential function; y_0 is the intercept (response value when $x=0$); a is the difference between the maximum and minimum values of the variable; and b is the slope of the curve.

A linear polynomial regression equation was found to be the most appropriate for modeling the mortality variable (Equation 3):

$$y = a + bx \quad (3)$$

where: y is the response variable of interest; x represents the collection times; a is the intercept or linear coefficient; and b represents the slope of the line.

The temporal dynamics of the seeds in the soil (measured in months) were evaluated based on the following variables: germination, mortality, viability (distinguishing between viable and non-viable seeds), and seed predation or deterioration, all calculated as averages.

3. Results and Discussion

3.1 Temperature and water potential

No seed germination was observed at 10, 35, 40, or 45 °C in the first experiment (Figure 1A) and at 40 or 45 °C in the second experiment (Figure 1B). In the second experiment, germination at 10, 15, and 35 °C was higher than in the first; however, in both experiments, germination at these temperatures remained lower compared to the other temperatures. For the remaining temperature conditions, cumulative germination data of hairy beggarticks seeds fitted the four-parameter Weibull sigmoidal model (Figure 1; Table 1). The R^2 values ranged from 0.97 to 0.99, and the MSE ranged from 3.7 to 8.5, indicating a satisfactory model fit. Germination percentages increased starting

at 20 °C, with delayed germination observed under mild temperatures (10–20 °C). Similar findings have been reported for hairy beggarticks populations from different regions of Brazil, where most samples germinated between 10 and 35 °C (Barros et al., 2017).

Based on the estimated T_{50} values (Table 1), the cardinal temperatures for hairy beggarticks germination were determined. The parameters of the linear equations fitted to the suboptimal and supraoptimal temperature ranges enabled the estimation of a T_b of $10.41 \text{ °C} \pm 0.03$, a T_o of $24.70 \text{ °C} \pm 0.04$, and a T_m of $41.85 \text{ °C} \pm 0.05$ (Figure 2A). For comparison, the T_m for an Australian population of hairy beggarticks was estimated under alternating temperature regimes of 25/15 °C or 30/10 °C (Chauhan et al., 2019), while for populations from different geographic regions, germination was highest at 15 °C (Barros et al., 2017).

In the water potential experiment, the maximum germination percentage decreased as the water potential declined (Figure 1C, Table 2). The cumulative germination curves were fitted to the Weibull function, with R^2 values of 0.98 and 0.99 and MSE ranging from 3.3 to 10.8, indicating a satisfactory model fit. Hairy beggarticks seeds showed higher germination rates under conditions of greater water availability. At water potentials between 0 and -0.2 MPa, approximately 80% of the seeds germinated (Figure 1C).

Decreasing water potential levels below -0.6 MPa (Figure 1C) led to germination rates falling below 20%, with no seed germination observed at lower water potentials. Complete inhibition of hairy beggarticks seed germination has also been reported at Ψ_b below -0.8 MPa when using saline solutions (Chauhan et al., 2019), likely due to enzymatic inhibition critical to the germination process (Marcos Filho, 2015). It is important to note that differences may arise when comparing water potential effects using saline versus PEG solutions, as NaCl can induce seed toxicity. Nonetheless, supporting Chauhan et al. (2019), the estimated Ψ_b for hairy beggarticks, based on the $1/T_{50}$ approach, was $-0.85 \text{ MPa} \pm 0.05$ (Figure 2B).

3.2 Mathematical modeling of the emergence

The climatic data varied across the three simulated sowing dates, particularly in terms of precipitation. Additionally, average daily temperatures were higher for the second and third simulated sowing dates (Figure 3A and B). Over the five-year analyzed, November—corresponding to the second simulated soybean sowing date—was consistently the driest month, with irregular rainfall totaling less than 50 mm. In the first year, higher cumulative precipitation occurred prior to October 20, along with smaller rainfall events that helped maintain soil water potential within a suitable range for seedling emergence during the first 10 days of monitoring (Figure 3C). Although similar small rainfall events were observed for the third simulated sowing date across the five years of monitoring, the overall low precipitation levels in November led to soil water potentials

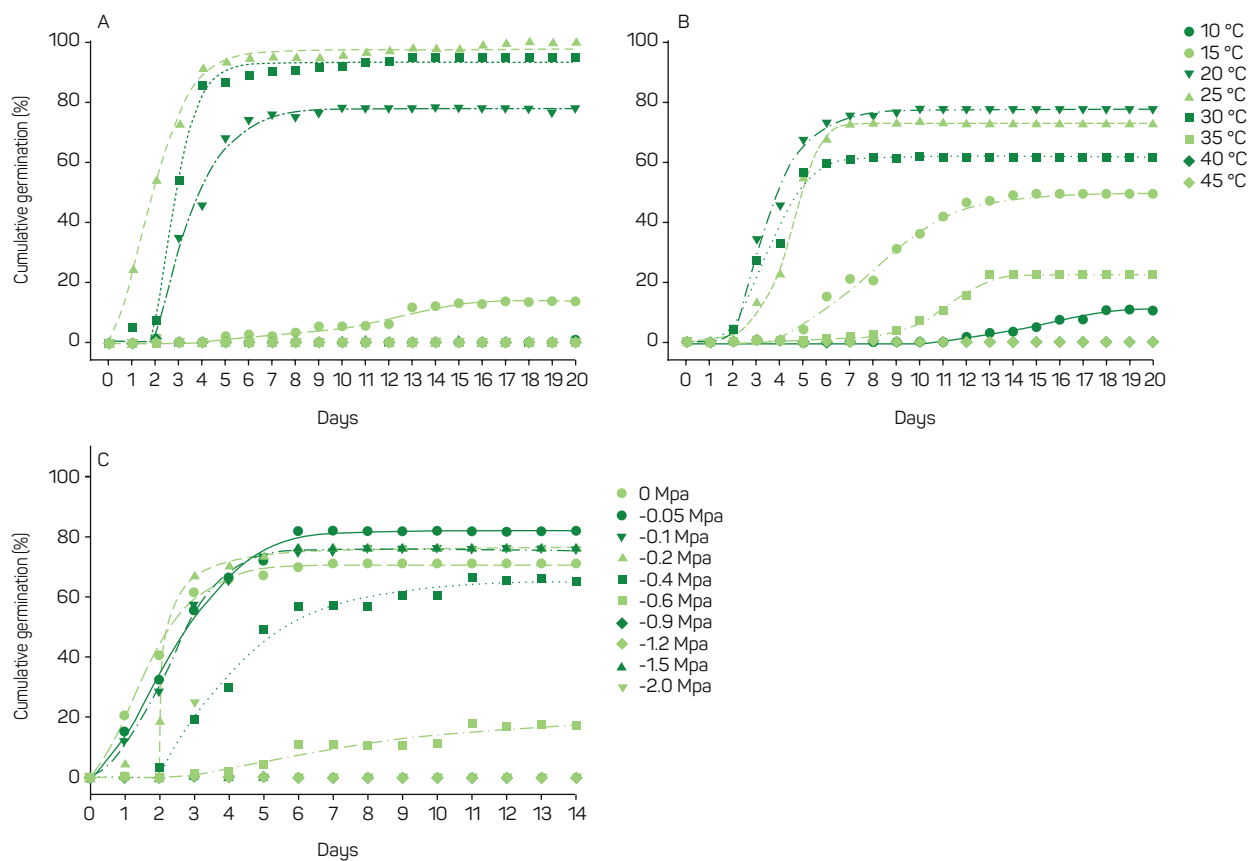


Figure 1 - Cumulative germination curves for hairy beggarticks in the first (A) and second experiments (B) under different constant temperatures, and in the third experiment (C) under different water potentials, as a function of time (in days). Lines were fitted to the Weibull model for each data series.

Table 1 - Estimated parameters (a, T ₅₀ , b, c) of the Weibull function fitted to seed germination data of hairy beggarticks at constant temperatures (T) of 10, 15, 20, 25, 30, 35, 40, and 45 °C									
First experiment									
T	a		T ₅₀		b		c		R ²
15 °C	13.50	± 0.43 ¹	11.10	± 0.35	1394.64	ns	473.68	ns	0.97
20 °C	77.64	± 0.63	3.31	± 0.07	1.89	± 0.14	1.19	± 0.13	0.99
25 °C	97.23	± 0.54	1.83	± 0.06	2.38	± 0.28	1.55	± 0.21	0.99
30 °C	92.96	± 0.63	2.79	± 0.06	1.30	± 0.16	1.37	± 0.25	0.99
Second experiment									
10 °C	11.23	± 0.83	15.14	± 0.27	8.01	± 2.68	3.02	± 1.49	0.99
15 °C	49.46	± 0.78	7.98	± 0.14	6.63	± 1.18	2.22	± 0.50	0.99
20 °C	77.64	± 0.63	3.31	± 0.07	1.89	± 0.14	1.19	± 0.13	0.99
25 °C	72.90	± 0.41	4.43	± 0.07	17.70	± 5.88	17.77	± 6.84	0.99
30 °C	61.62	± 0.63	3.50	± 0.10	3.28	± 1.03	2.41	± 0.89	0.98
35 °C	22.65	± 0.25	11.04	± 0.14	1745.58	ns	1131.28	ns	0.99

T: temperature [°C]; a: maximum recorded emergence percentage; b: rate of increase; c: shape parameter; T₅₀: time (in days) required to reach 50% germination or emergence; R²: coefficient of determination; NS: non-significant parameter. ¹ Values represent the standard error of the mean. Temperatures not listed did not show germination, so regression could not be adjusted.

Table 2 - Estimated parameters (a, T_{50} , b, c) of the Weibull function fitted to seed germination data of hairy beggarticks at water potentials 0, -0.05, -0.1, -0.2, -0.4, -0.6, -0.9, -1.2, -1.5, and -2.0 MPa

Water potential	a		T_{50}		b		c		R ²
0.00 MPa	81.7	± 0.591 ¹	2.33	± 0.06	3.12	± 0.32	1.78	± 0.22	0.99
-0.05 MPa	70.3	± 0.42	1.65	± 0.05	2.21	± 0.22	1.66	± 0.19	0.99
-0.1 MPa	75.6	± 0.55	2.28	± 0.06	3.04	± 0.54	2.32	± 0.49	0.99
-0.2 MPa	74.5	± 0.88	2.09	± 0.06	0.23	± 0.11	0.47	± 0.14	0.99
-0.4 MPa	65.0	± 1.70	3.91	± 0.15	2.83	± 0.35	1.23	± 0.23	0.99
-0.6 MPa	24.1	± 10.3	8.76	± 7.56	8.73	± 6.32	1.04	± 0.74	0.98

a: maximum recorded emergence percentage; b: rate of increase; c: shape parameter; T_{50} : time (in days) required to achieve 50% germination or emergence; R²: coefficient of determination; ¹ Values represent the standard errors of the mean. Water potentials not listed did not show germination, so regression could not be adjusted.

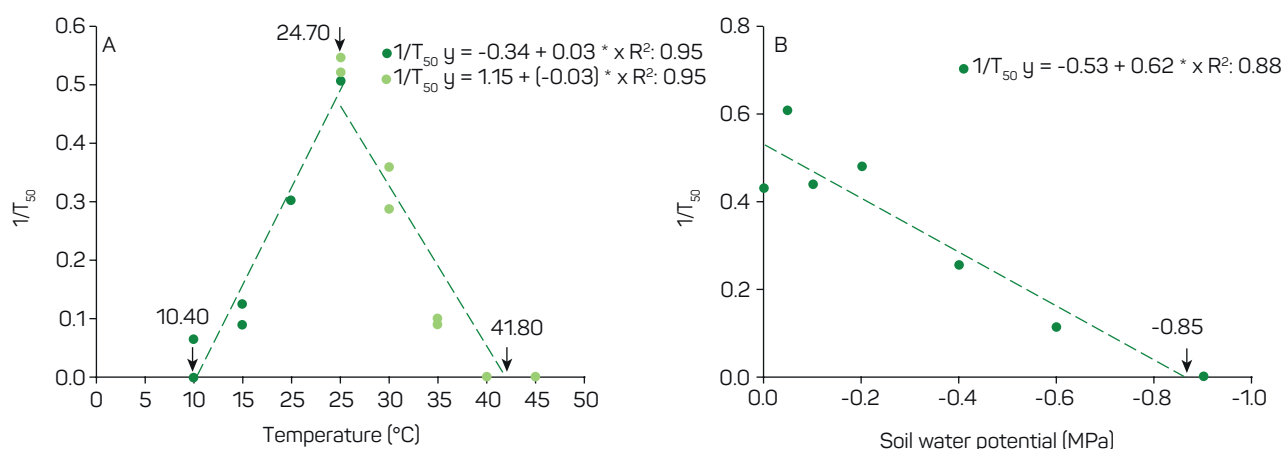


Figure 2 - Regression line fitted to $1/T_{50}$ results in the sub-optimal and supra-optimal temperature ranges and in response to different temperatures (A), or water potentials (MPa) (B) for hairy beggarticks. Filled and empty symbols represent the observed data from the first and second experiments, respectively, and the lines are the fitted linear regressions.

that were inadequate, or marginal at best, for seedling emergence (Figure 3C).

Precipitation, combined with rising average daily temperatures, stimulates new weed emergence. However, due to low accumulated water volumes in the soil and irregular rainfall distribution, soil water potential varied across years (Figure 3C). This interannual variability in precipitation and its impact on soil water potential is particularly valuable for developing predictive models tailored to the region's microclimate (Royo-Esnal et al., 2015).

By accounting for the emergence of hairy beggarticks in relation to environmental variability, it was possible to develop an emergence model for the species based on TT and HT. Both models described emergence across the three monitoring periods using a four-parameter sigmoidal Weibull function (Figure 4). The models exhibited similar predictive performance for each simulated sowing date. However, the TT-based model predicted emergence in a more staggered pattern, whereas the HT-based model

predicted faster emergence over a shorter duration. This similarity in predictive responses can be attributed to the large dataset and the interannual variability captured across different years. Furthermore, the soil water potential only occasionally dropped below the Ψ_b of the species.

Although the TT model showed a satisfactory fit, some parameters were not statistically significant for hairy beggarticks emergence in November (the second simulated sowing date), and this model also had the lowest R² value observed (Model C; Table 3). In contrast, the HT model demonstrated greater accuracy, with better fit across all monitoring periods. This improved performance is attributed to the HT model accounting for water potential and temperature accumulation, rather than relying solely on T_b , as both models began accumulating temperature from the start of the experiment. These higher R² values and lower standard errors observed in the HT models (Table 3) further confirm their superior predictive performance.

These findings suggest that HT models are more accurate than TT models for predicting weed emergence,

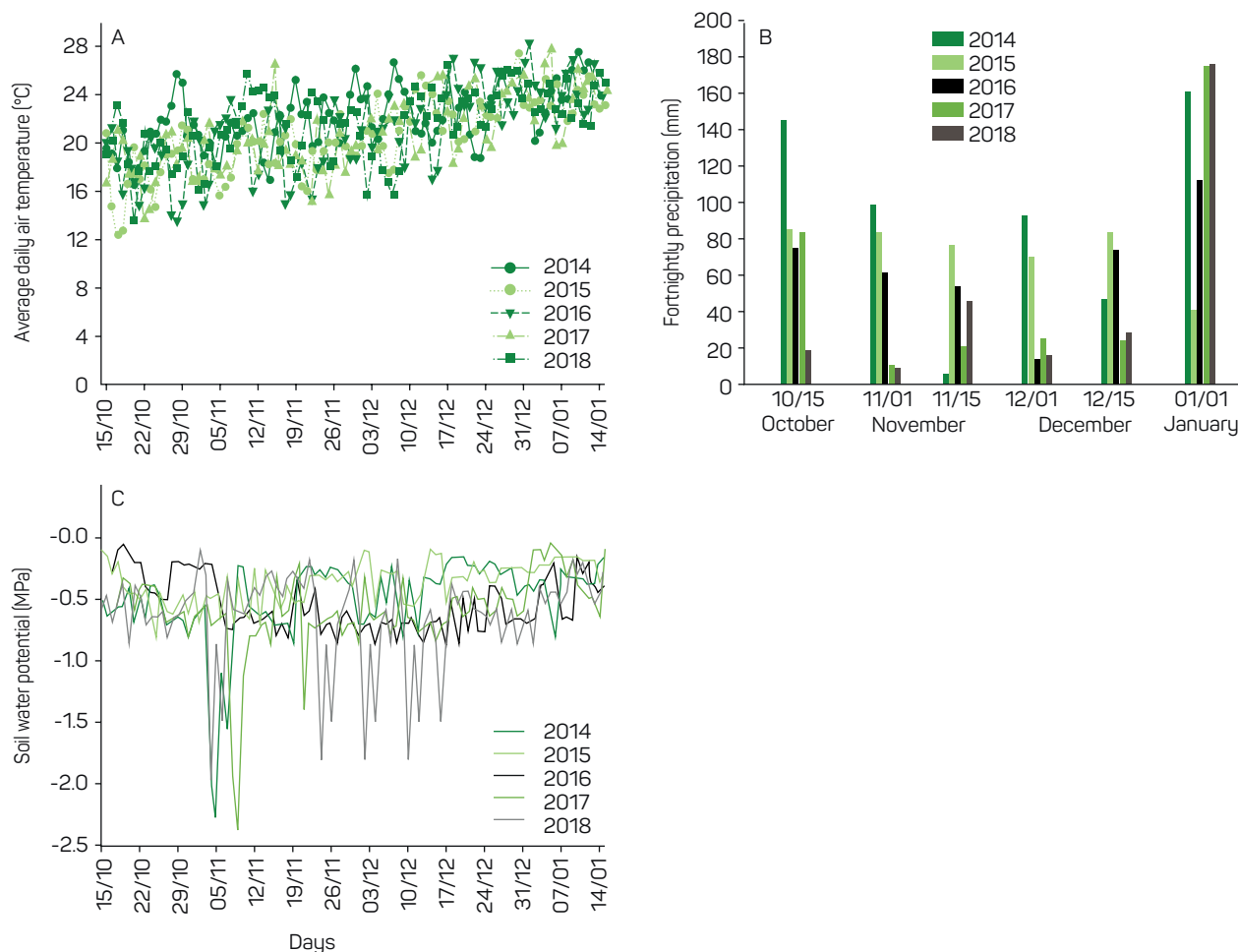


Figure 3 - Climatic data observed in the experimental area in Capão do Leão (RS) during the experiment: daily average air temperature (A), accumulated precipitation for 15 days (B), and daily soil water potential (MPa) during the years 2014, 2015, 2016, 2017 and 2018.

especially in regions where periods of water deficit occur (Leguizamón et al., 2005). Moreover, studies have shown that HT models can improve prediction accuracy even under adequate soil moisture conditions, as observed for *Helianthus annuus* L. (Werle et al., 2014). Similarly, the HT model was found to outperform the TT model in predicting the emergence of *Conyza bonariensis* L. (Zambrano-Navea et al., 2013).

The emergence of hairy beggarticks was generally highest in October (the first simulated sowing date) across the three sowing periods (Figure 4). This pattern has been reported for various weed species, including Poaceae and eudicots (Zandoná et al., 2018b), and is typically associated with greater success in the establishment and perpetuation of species. However, it is noteworthy that in the years 2014, 2017, and 2018, the greatest emergence of hairy beggarticks occurred during the third simulated sowing date (Figure 4E and F).

Until mid-November (the second sowing date), the emergence of hairy beggarticks occurred steadily. In contrast,

emergence in December (the third sowing date) may have been influenced by various, leading to a faster emergence rate. This pattern is more clearly observed in the dispersion of the accumulated emergence data points for the third simulated sowing date (Figure 4E and F), as well as in the lower values of coefficients *a* and *c* in the models (Table 3).

Precisely identifying the causes behind increases or decreases in weed emergence is challenging, as multiple factors may be involved. Key elements include climatic variations across simulated sowing dates and years (Figure 3), the absence of soil tillage, the presence of oat straw as ground cover, and seed dormancy conditions—all of which likely influenced weed emergence and establishment. Still, species density in the field is critical for assessing competitive potential (Balbinot Jr et al., 2003). The highest density of hairy beggarticks plants was observed during the second simulated soybean sowing date, averaging 41 plants m^{-2} (Figure 4C and D). It is important to note, however, that even at low densities, such as 8 plants m^{-2} , hairy beggarticks can reduce soybean yield by up to 10% (Rizzardi et al., 2003).

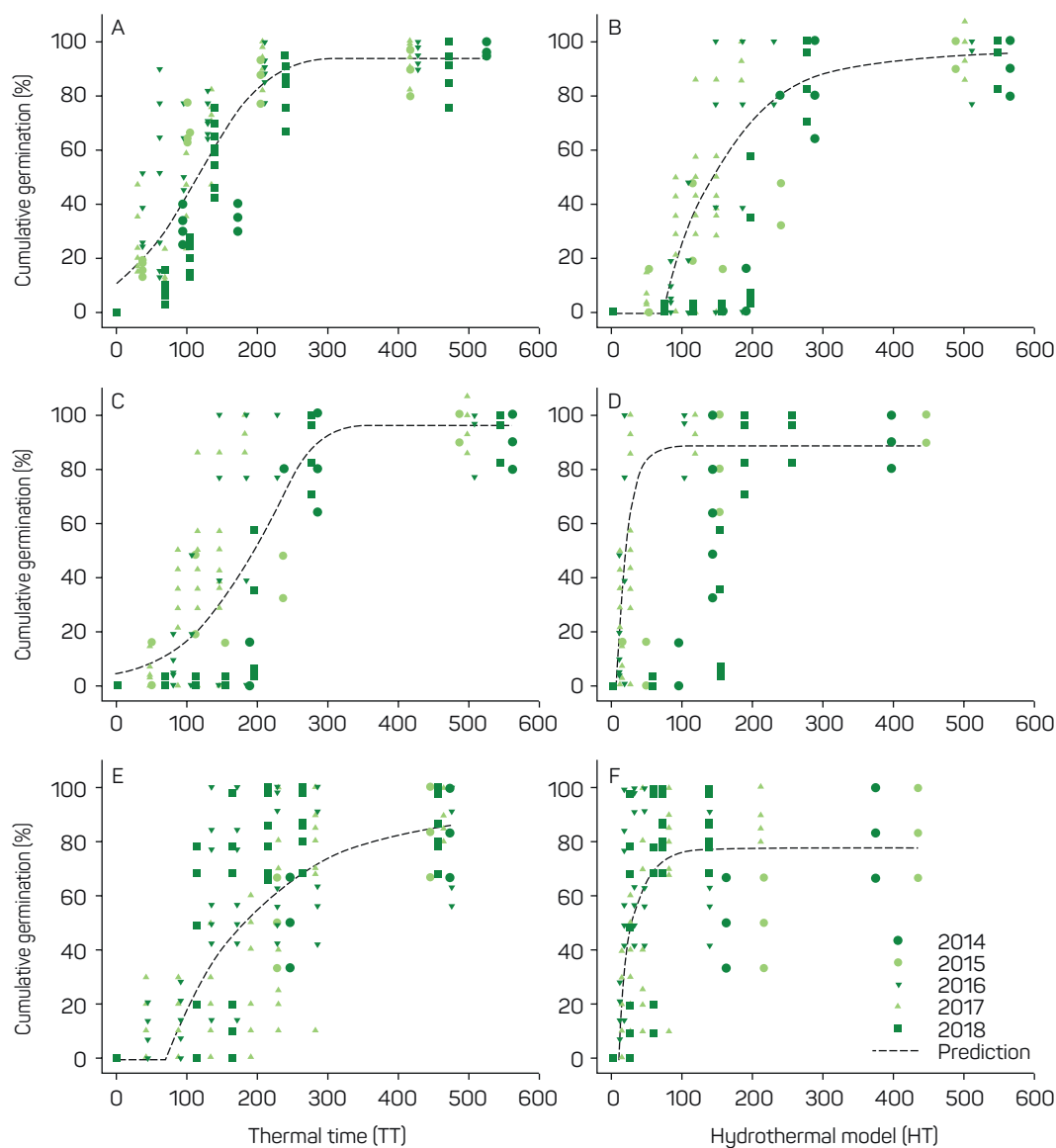


Figure 4 - Thermal (A, C, and E) and hydrothermal (B, D and F) time models for cumulative emergence (%) of hairy beggarticks during the first (A and B), second (C and D), and third (E and F) emergence events in the growing seasons of 2014, 2015, 2016, 2017, and 2018 in Capão do Leão, Rio Grande do Sul, Brazil. Dashed lines represent predicted emergence, and symbols indicate observed emergence.

Table 3 - Estimated parameters (a, T ₅₀ , b, c) of the Weibull function fitted to the thermal and hydrothermal time model for seed germination of hairy beggarticks									
Model	a		T ₅₀		b		c		R ²
A	93.94	± 2.87 ¹	107.44	± 5.83	355.27	± 29.99	4.54	± 0.59	0.85*
B	96.05	± 5.02	137.61	± 8.29	101.01	± 16.92	1.08	± 0.27	0.87*
C	95.91	± 5.28	191.08	± 15.66	112551.66 ns		16091.86 ns		0.63*
D	88.53	± 2.56	16.25	± 1.24	15.88	± 4.04	1.06	± 0.49	0.74*
E	90.27	± 12.29	162.70	± 19.72	133.02	± 31.61	1.01	± 0.61	0.70*
F	78.17	± 4.57	17.89	± 2.27	17.37	± 4.12	0.73	± 0.20	0.77*

T: temperature (°C); a: maximum recorded emergence percentage; b: rate of increase; c: shape parameter; T₅₀: thermal (A, C, and E) or hydrothermal (B, D, and F) time required to achieve 50% germination or emergence; R²: coefficient of determination. * The model is significant. NS: non-significant parameter. ¹ Standard error. A and B refer to the first simulated sowing date; C and D to the second; and E and F to the third, for thermal and hydrothermal times, respectively.

The emergence model for hairy beggarticks appears robust and potentially useful as a tool for weed management, partly due to the large dataset used since larger datasets typically allow for more accurate parameter estimation. Nonetheless, models based on large and complex datasets are not always complete or fully reliable (Colbach et al., 2006). A key advantage of using the HT model over the TT model is its ability to account for temporary pauses in emergence caused by low soil moisture, an important factor in minimizing prediction error when applying the model in practice (Masin et al., 2014).

For the first simulated sowing date, a post-emergence herbicide with residual activity is recommended due to the slower emergence pattern. For the November (second) and December (third) simulated sowing dates, a burndown treatment combined with a pre-emergence herbicide is necessary to ensure residual control and to allow for the crop's initial development in weed-free conditions. Additionally, these models can serve as valuable tools for planning weed management strategies across a range of summer crops grown under no-tillage systems.

3.3 Longevity and persistence of seed bank

Data analysis revealed a significant interaction between burial depth and retrieval time only for the variable remaining seeds. In contrast, the variables germination, dormancy, mortality, and persistence were influenced primarily by retrieval time (Figure 5). For the remaining seeds, a consistent decline was observed over time across all burial depths, with data fitting a decreasing exponential regression model (Figure 5A). The number of recovered seeds decreased considerably after 10 months of burial. By the final assessment at 16 months, only 3.2, 5.5, and 9% of seeds remained at burial depths of 0, 3, and 6 cm, respectively, with no statistically significant differences among depths due to overlapping confidence intervals of the means.

Hairy beggarticks seeds showed approximately 80% germination at retrieval moment 0 (Figure 5B), indicating that only 8.3% of them were dormant at the time of burial (Figure 5C). At two and four months after burial, about 43% of the retrieved seeds germinated under laboratory conditions; however, germination rates declined to near zero in subsequent evaluations (Figure 5B). Such results may be associated with the increasing mortality of the remaining seeds, which showed a linear trend over time (Figure 5D), reaching approximately 10% after 16 months. At the final retrieval, most seeds did not exhibit viability in the tetrazolium test, resulting in persistence close to zero for all burial depths (Figure 5E), suggesting that the species has a transient seed bank in the soil.

The primary source of future weed infestations is the seed bank (Cechin et al., 2021b). This seed bank is dynamic, with inputs occurring through immigration or through seed production and dispersal within the area (Cechin et al.,

2021a). Outputs, in turn, result from processes such as germination, aging, loss of viability, predation, and decay (Chauhan, Johnson, 2010). For hairy beggarticks, seed bank outputs were high, as reflected in the data on remaining seeds and mortality (Figure 5A and D). This highlights the need for annual replenishment of the seed bank. After 16 months of burial, only about 5% of seeds were recovered, with a low germination level (Figures 5A and B). Seed bank losses in hairy beggarticks were primarily attributed to high levels of predation and seed decay across burial depths, reaching nearly 100% at 0 cm (Figure 6A) and about 90% at 6 cm (Figure 6C).

Dormant seeds were not considered a major factor in the persistence of hairy beggarticks seeds in the soil, as no more than 5% of buried seeds were dormant between two and four months after burial (Figure 6). Similar patterns have been observed for ryegrass (*Lolium multiflorum*), where dormancy dropped below 20% within 60 days of burial (Cechin et al., 2021a). In contrast, horseweed (*Conyza* spp.) exhibited peak dormancy levels around three months post-burial (Vargas et al., 2018). Meanwhile, seed mortality remained relatively constant and accounted for the proportion of recovered seeds that were no longer viable (Figure 6). Given these findings, management practices that effectively limit germination and emergence may prove successful, as hairy beggarticks shows limited persistence in the soil seed bank.

3.4 Practical implications

Understanding the germination process and seed bank dynamics of hairy beggarticks, along with its emergence modeling, represents a significant advance in weed science. This knowledge lays the foundation for developing more effective management strategies. The species shows a wide germination range, with a T_b of 10.4°C and a T_{max} of 41.9°C. It also tolerates low soil moisture, germinating at a Ψ_b of -0.85 MPa. These traits highlight its remarkable adaptability to various environmental conditions.

Armed with this information, farmers can make more strategic decisions. For example, using pre-emergent herbicides during early sowing can be particularly effective. Early in the season, slower crop emergence may allow hairy beggarticks to establish earlier and gain a competitive edge. In such scenarios, weed emergence modeling becomes a helpful tool for optimizing the timing of control measures.

TT and HT models accurately predicted hairy beggarticks emergence under different soybean sowing dates and therefore can be integrated into digital tools to support weed management in cropping systems. Despite their potential, predictive models are still rarely applied in practice. Nevertheless, they offer valuable support for weed monitoring and decision-making in the field. Modeling also provides a strong foundation for future research on the management of this species. Given that weed infestations

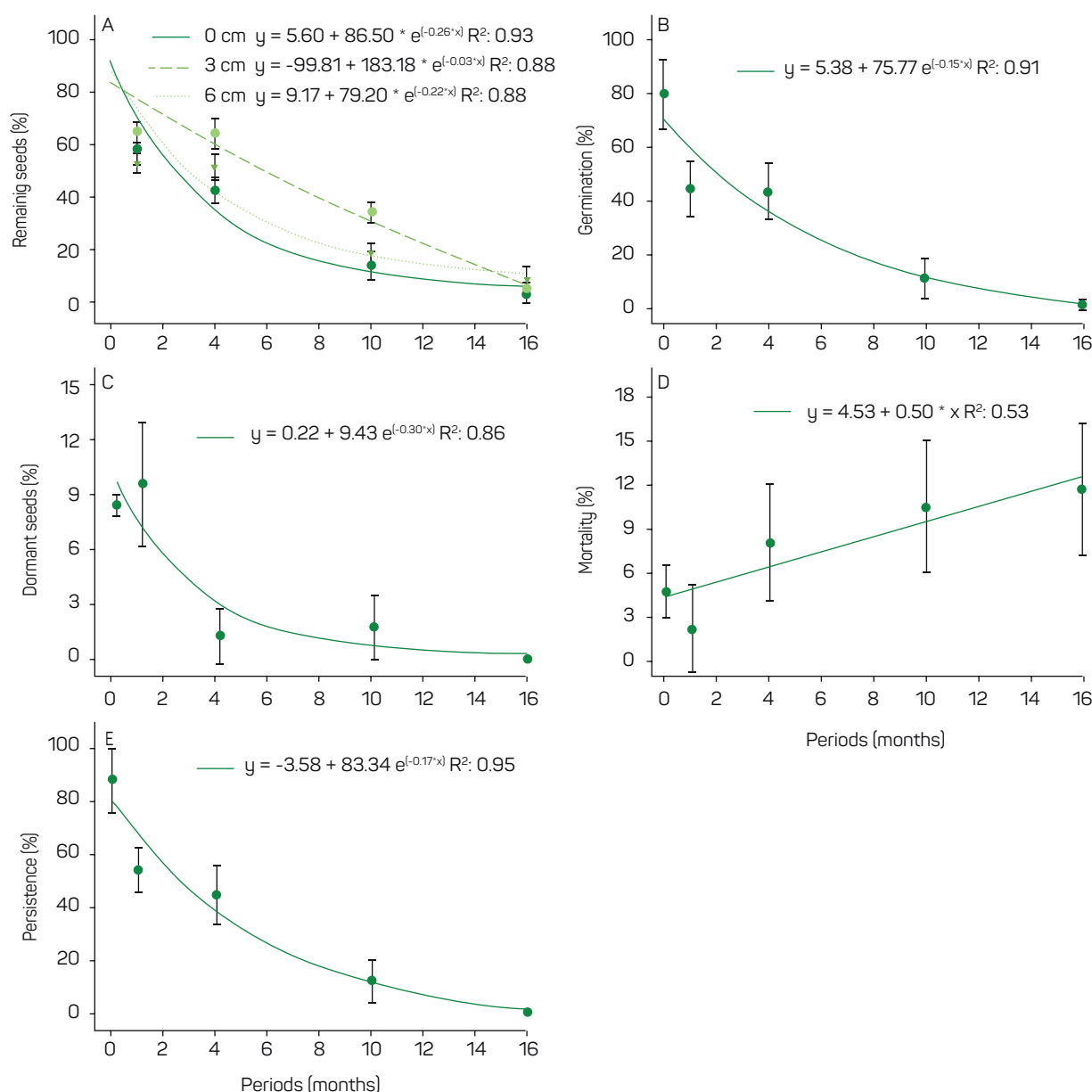


Figure 5 - Percentage of remaining seeds (A), germination (B), dormancy (C), mortality (D), and persistence (E) of hairy beggarticks after germination tests, as a function of burial depth and collection time (in months). Dots represent average values of replicates at each depth and retrieval time, and the bars show the respective 95% confidence intervals. July corresponds to burial time, defined as month zero.

often originate from the soil seed bank, understanding its dynamics is essential.

Strategies that prevent seedling emergence, combined with proper control of emerged plants, are key to reducing seed bank inputs and minimizing future infestations. The findings for this species enable the development of management strategies adapted to local climatic conditions. These should consider periods favorable to hairy beggarticks emergence across different crop sowing dates and inform the optimal timing and placement of pre- and post-emergence herbicide applications. Furthermore, a

better understanding of the seed bank dynamics of hairy beggarticks seeds enables the adoption of management strategies aimed at reducing its persistence in the soil.

4. Conclusions

Tb, To, and Tmax for hairy beggarticks emergence were determined to be 10.4, 24.7, and 41.9 °C, respectively. In addition, the Ψ_b was estimated at -0.85 MPa. These findings provide critical ecophysiological parameters for understanding the emergence dynamics of this important weed species.

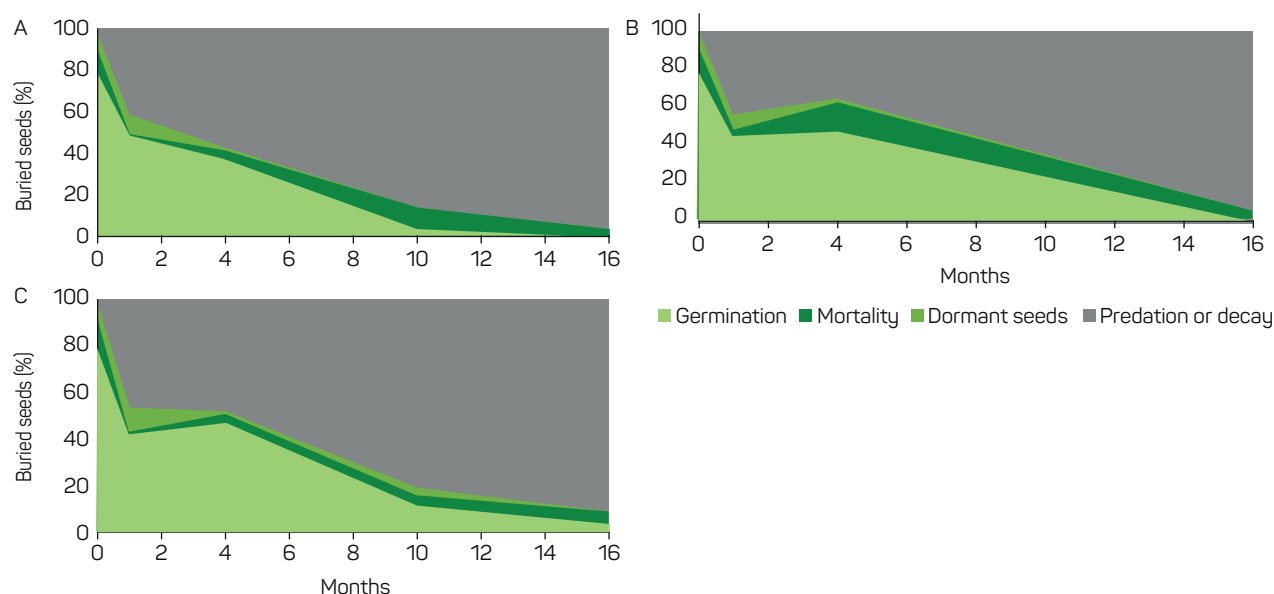


Figure 6 - Changes over time (in months) in the condition of hairy beggarticks seeds in the soil, as a function of collection time and depth—0 cm (A), 3 cm (B), and 6 cm (C)—analyzed for germination, mortality, dormancy, and predation or decay. July corresponds to burial time, defined as month zero.

Both TT and HT models performed well in predicting emergence patterns of hairy beggarticks under varying environmental conditions, highlighting their potential as reliable tools to support IWM strategies, particularly in optimizing the timing of control interventions based on environmental conditions.

The present study confirmed that hairy beggarticks maintains a transient seed bank, with substantial seed losses due to predation and decay. This ecological trait can inform seed bank-based management practices, including the optimal timing and frequency of tillage and herbicide applications.

Overall, the models and biological insights presented in this study enhance our understanding of the emergence ecology of hairy beggarticks. These findings can support the development of predictive modeling approaches and guide more sustainable, site-specific weed control measures in cropping systems where this species poses a challenge.

Author's contributions

All authors have read and agreed to the published version of the manuscript. RRZ, FAPG, SP, ARU, and DA:

conceptualization and methodology. RRZ, FAPG, and DA: data collection and curation. RRZ, FAPG, and DA: data analysis. RRZ, FAPG, SP, ARU, and DA: data interpretation. RRZ, and DA: funding acquisition and resources. RRZ, and DA: project administration. ARU, and DA: supervision. RRZ, FAPG, and DA: writing – original draft. SP, and ARU: writing – review and editing.

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