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Original Article

Modeling Drought Effect on Seed Dormancy and Germination in Winter Wild Oat (*Avena sterilis* subsp. *ludoviciana*)

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Abstract

Understanding and predicting the emergence of winter wild oat *(Avena sterilis* subsp. *ludoviciana* (Durieu.) Gillet & Magne) under changing climate conditions are vital for effective management, yet the combined effects of burial duration and soil moisture on its environmentally driven seed dormancy and germination remain poorly quantified, particularly in arid and semi-arid regions. This study aimed to examine the effects of soil moisture during seed burial on dormancy release and germination dynamics of *A. sterilis* subsp. *ludoviciana*. A factorial experiment in a randomized complete block design (RCBD) with three replications was conducted over two consecutive cropping seasons (2021–2023). Treatments included seed type (intact with hull vs. dehulled), burial duration (1–5 months), and five soil water potentials (0 to −0.8 MPa). Seeds were incubated under controlled temperatures in an incubator reflecting historical soil conditions, and germination was evaluated at six incubation temperatures (5–30 °C) in germinator. Fractional cumulative germination was modeled using a modified Triangle Area Model (TAM) that incorporates the combined effects of burial duration, soil temperature, and moisture. The results showed that burial duration had the greatest influence on germination, followed by soil water potential and temperature. Dehulled seeds germinated more rapidly than intact seeds, indicating the regulatory role of the hull. Maximum germination (~85%) occurred at −0.3 MPa and 15°C, whereas severe drought (−0.8 MPa) reduced germination, suggesting a mechanism for dormancy maintenance under unfavorable conditions. The modified TAM accurately simulated germination dynamics across treatments, achieving an R^2 of 0.88 and an RMSE of 0.01. Prolonged burial under sufficient moisture progressively reduced dormancy, reflecting interactions between physical and physiological dormancy. The results suggest that summer drought periods, together with the absence of irrigation and the use of summer fallow, may delay the timing of germination in winter wild oat. Although weeds are continually adapting to environmental conditions, drought induced by climate change may promote the emergence of more drought-tolerant forms and lead to shifts in weed emergence flushes in crop fields.

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مقاله پژوهشی

مدلسازی اثرات خشکسالی بر پویایی خواب و جوانه زنی بذر یولاف وحشی زمستانه (*Avena sterilis* subsp. *ludoviciana*)

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چکیده

درک اثرات ترکیبی عوامل محیطی بر خواب و جوانه‌زنی بذر برای پیش‌بینی ظهور علف‌های هرز در شرایط تغییر اقلیم به‌ویژه در مناطق خشک و نیمه‌خشک، امری ضروری است. در این پژوهش، تغییرات خواب بذر علف‌هرز یولاف وحشی زمستانه در پاسخ به سطوح رطوبت خاک در طول زمان دفن بذر در قالب یک آزمایش فاکتوریل طی دو سال زراعی (۱۴۰۱-۱۴۰۰ و ۱۴۰۲-۱۴۰۱) مورد بررسی قرار گرفت. تیمارها شامل نوع بذر (با پوشینه و بدون پوشینه)، پتانسیل رطوبتی خاک (صفر، ۰/۸-، ۰/۴-، ۰/۲- و ۰/۳- مگاپاسگال) و ۵ دوره زمانی دفن (۱ تا ۵ ماه) بودند. برای پیش بینی جوانه زنی یولاف، اثر زمان دفن و رطوبت خاک به عنوان زیر-مدل به مدل مساحت مثلث «TAM» به عنوان مبنای محاسبه واحدهای زمان-دمایی، اضافه شد و برای پیش‌بینی جوانه‌زنی تجمعی بذر در بازه دماهای جوانه‌زنی از ۵ تا ۳۰ درجه سانتیگراد (به فاصله ۵ درجه) کالیبره شد. مدل حاصل، با دقت بالایی الگوهای جوانه‌زنی را پیش‌بینی کرد (R2 = ۰/۸۸ و RMSE= ۰/۰۱). براساس نتایج، طول دوره دفن عامل اصلی تغییرات در جوانه‌زنی بذر این گونه شناخته شد. پتانسیل رطوبتی خاک اگرچه اثر معنی داری نشان داد ولی در درجه بعدی اهمیت قرار گرفت. اثر این عوامل بر بذرهای بدون پوشینه، بصورت معنی‌داری بالاتر بود. بیشترین میزان جوانه‌زنی در پتانسیل آبی ۰/۳- مگاپاسکال و دمای ۱۵ درجه سانتی گراد مشاهده شد. با کاهش پتانسیل آب به ۰/۸- مگاپاسکال، جوانه‌زنی در تمامی دماها به طور معنی‌داری کاهش یافت. طولانی‌شدن دوره دفن، در صورت وجود رطوبت کافی، نیز به تدریج باعث افزایش جوانه‌زنی تجمعی و کاهش خواب بذر شد. با توجه به نتایج، به نظر میرسد دوره های خشکی در تابستان و یا عدم آبیار ی و آیش گذاشتن مزرعه در کشت تابستانه، موجب تأخیر در زمان جوانه زنی یولاف زمستانه می گردد. البته علف های هرز همواره در حال ایجاد سازگاری با شرایط هستند ولی احتمالاً بروز خشکی حاصل از پدیده تغییرات اقلیم، باعث ظهور گونه های مقاوم تر به خشکی و تغییراتی در موجهای رویش علف های هرز در مزارع بشود.

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Introduction

Seed dormancy and germination are central processes that determine the timing of weed emergence and influence crop–weed interactions. Environmental cues, particularly temperature and soil moisture, regulate dormancy release and germination. Many weed species exhibit both physiological and physical dormancy mechanisms, which delay germination and enhance survival under variable environmental conditions (Baskin & Baskin, 2021). Physiological dormancy is gradually alleviated in response to environmental signals, while physical dormancy results from impermeable seed coats that restrict water uptake (Lamont & Pausas, 2023).

In natural soils, seeds experience fluctuating temperature and moisture regimes that drive transitions between dormant and nondormant states. Soil temperature signals seasonal changes and regulates physiological processes involved in dormancy release, whereas soil moisture determines water availability required for metabolic activation and germination (Walck et al., 2011). Cold stratification generally facilitates dormancy break in summer annuals, whereas warm stratification (>15 °C) promotes dormancy release in winter annuals (Just et al., 2023). Climate change, characterized by rising temperatures and reduced precipitation, is altering these environmental cues, with potential consequences for germination timing, seedling emergence, and population dynamics (Varanasi et al., 2016; Hufnagel & Garamvolgyi, 2014).

Winter wild oat (*Avena sterilis* subsp. *ludoviciana*) is a widely distributed winter annual weed that poses significant agronomic challenges, including in Iran, where regional variation in temperature and precipitation strongly influences seed dormancy and germination dynamics (Oveisi et al., 2025a; Yazdanipour et al., 2023). The species exhibits substantial morphological and physiological diversity, enabling adaptation to a broad range of climatic conditions (Oveisi et al., 2024b). Germination traits are closely linked to seed morphology and are strongly regulated by environmental factors, particularly temperature and soil moisture (Oveisi et al., 2025a). However, quantitative understanding of how these factors interact during seed burial to control dormancy release and germination timing remains limited, restricting predictive modeling of weed emergence and the development of optimized management strategies (Norsworthy & Oliveira, 2007; Dorado et al., 2009).

Thermal time models, which integrate accumulated temperatures above a base threshold, are commonly applied to predict germination patterns (Calvache et al., 2021). Yet, most existing models do not fully account for the combined effects of soil moisture and burial duration on dormancy release, reducing their predictive accuracy under field conditions. To address this limitation, we simulated germination dynamics in winter wild oat by integrating thermal time, soil moisture, and burial duration using the Triangle Area Model (TAM; Oveisi et al., 2024a).

Based on this framework, we tested two hypotheses: (1) reduced soil moisture during burial delays dormancy release and germination; and (2) dormancy alleviation and germination patterns are significantly influenced by soil temperature–moisture interactions during burial. The aim of this study was to quantify the joint effects of burial duration, soil moisture, and temperature on seed dormancy and germination, providing a predictive basis for emergence timing and informing weed management strategies under changing climatic conditions.

Materials and Methods

Experimental Design and Treatments: To investigate the effects of soil moisture during burial on seed dormancy and germination dynamics of winter wild oat, a factorial experiment was conducted using a randomized complete block design with three replications over two consecutive cropping seasons (2021–

2022 and 2022–2023). The experimental factors included: 1) *seed type:* intact seeds with hull vs. dehulled seeds, 2) *soil water potential:* 0, −0.03, −0.2, −0.4, and −0.8 MPa, and 3) *burial duration:* 1, 2, 3, 4, and 5 months. Mature seeds of winter wild oat were collected from 17 wheat fields in Karaj, Iran (35°48′ N, 50°57′ E) in mid-June 2022 and 2023. Seeds were collected from at least 50 mature plants across multiple locations, including cultivated fields and field margins, and were stored in paper bags at room temperature (20–25 °C) for approximately 15 days prior to the start of the experiment. The seeds were pooled to minimize variance from the conditions of the mother plants, then air-dried, cleaned, and prepared in sufficient quantities for the experiment. A portion of the seeds was manually dehulled to remove the lemma and palea in order to evaluate the role of physical dormancy.

Soil Preparation and Moisture Adjustment: Soil samples were collected from the topsoil of wheat fields, air-dried, and sieved to remove debris before being placed into pots for the burial experiment. For each treatment combination, five small mesh bags (4 × 3 cm) were prepared (five replication), each containing 500 seeds. The bags were sewn to ensure complete contact between seeds and the surrounding soil while allowing easy removal, and each was equipped with a 20 cm-long string for retrieval. Target soil water potentials were established using a pressure plate apparatus. The volume of distilled water needed to achieve the desired water potential in the specific soil mass was calculated and added to each pot. To minimize evaporation, pots were covered with plastic bags and weighed daily. Whenever a decrease in pot weight was observed, the required amount of distilled water was added to maintain the target soil water potential.

Temperature Simulation and Germination Testing: Mean monthly soil temperatures for the period from July to November were obtained from the University of Tehran weather station based on a 10-year record (2011–2021). These data were used to simulate seasonal soil temperature conditions during seed burial. Five constant incubator temperatures were applied to represent monthly averages: 28 °C for July and August, 25 °C for September, 18 °C for October, and 11 °C for November. Throughout the burial period, incubators were maintained at the corresponding monthly temperature under a 12 h light/12 h dark photoperiod. At the end of each month, one mesh bag per pot was retrieved. Seeds were surface-washed with distilled water, disinfected in 1% sodium hypochlorite for 1 min, and rinsed three times with distilled water. For germination testing, 50 seeds from each mesh bag were placed in 10-cm-diameter Petri dishes lined with two layers of Whatman No. 1 filter paper. Five milliliters of distilled water were added to each dish to initiate and maintain moisture. Petri dishes were then incubated in a germinator at six constant temperatures (5, 10, 15, 20, 25, and 30 °C). Seed germination was recorded daily for 14 days, and final germination percentages were calculated. The experiment was conducted over two consecutive years, with 900 mesh bags used per year, representing all combinations of two seed types, five burial durations, five soil moisture levels, six germination temperature regimes, and three replications (2 × 5 × 5 × 6 × 3).

Model development: Here, we follow the triangle area model (TAM; Oveisi et al., 2024a), in which the thermal time accumulated for germination is estimated from the area of right-angled triangles. To model cumulative fractional germination (CGF), the effects of burial duration, soil temperature, and soil moisture were integrated. The TAM represents thermal time as a right-angled triangle, where the base corresponds to the time receiving a given temperature and the height (G_t) represents cumulative germination at time (t) and temperature (T). The method for calculating the triangle's base depends on whether the temperatures are sub-optimal or supra-optimal. For sub-optimal temperatures ($T < T_o$) and supra-optimal temperatures ($T > T_o$), the base is determined as follows:

$$Base_{sub} = (T - T_b) \times t_g \quad (1)$$
$$Base_{sup} = (T_c - T) \times t_g$$

The height of the triangle, G_t, represents cumulative fractional germination at a given time and temperature. To address the decreased germination efficiency that occurs when the temperature deviates from the optimum (T_o), two adjustment factors were applied:

$$HA_{subT} = HA_{sub} \times \left(1 - \frac{(T_o - T)}{(T_o - T_b)}\right) \quad (2)$$
$$HA_{supT} = HA_{sup} \times \left(1 - \frac{(T - T_o)}{(T_c - T_o))}\right)$$

where HA_{subT} and HA_{supT} are adjusted coefficients for sub-optimal and supra-optimal temperatures, respectively, reducing germination efficiency as the temperature deviates from T_o. Dormancy release and germination were further influenced by soil temperature thresholds (STT), soil moisture effects ($G_{(\theta)}$), and burial duration (G_{BT}).

These environmental cues were incorporated into the model as STT: The soil temperature threshold below which germination does not occur; $G_{(\theta)}$: The germination response to soil moisture, where θ_{50} is the moisture level at which 50% of G_{max} occurs, θ is the actual soil moisture, and $G_{(BT)}$ represents the sigmoidal response of germination to burial duration, with G_{max}, BT_{50}, and b_{BT} as parameters.

After evaluating multiple approaches for integrating the effects of temperature, moisture, and burial duration including linear weighting, multiplicative formulations, and alternative averaging schemes, the geometric mean was identified as the most appropriate method, providing the best agreement with observed germination responses and underlying biological principles.

$$G_{t.w.b} = \sqrt[3]{G_{st} \cdot G_{sw} \cdot G_{BT}} \quad (3)$$

Thermal time was calculated separately for three temperature zones:

Suboptimal zone ($T_b < T < T_{O1}$):

$$\frac{TT_{sub} = (T - T_{b(g)}) \cdot HA_{sub} \cdot G_{t.w.b} \cdot t}{2} \quad (4)$$

Optimal zone ($T_{O1} \leq T \leq T_{O2}$):

$$\frac{TT_{opt} = (T - T_{o1}) \cdot G_{t.w.b} \cdot t}{2} \quad (5)$$

Supra-optimal zone ($T_{O2} < T < T_c$):

$$\frac{TT_{sup} = (T_{b(g)} - T_{O2}) . HA_{sup} \cdot G_{t.w.b} \cdot t}{2} \quad (6)$$

Cumulative germination was modeled using a Weibull cumulative distribution function based on thermal time:

$$CGF\ (TT) = 1 - exp\left[-\left(\frac{TT}{a}\right)^{\beta}\right] \quad (7)$$

where alpha (α) is the scale parameter (thermal time to achieve ~63% germination), and beta (β) is the shape parameter defining the slope of the germination curve.

Statistical Analysis

A mixed-model analysis was used to evaluate the effects of treatments and their interactions on daily germination. Year was included as a random effect, along with blocks nested within years. Burial period, soil moisture, and germination temperature were considered as fixed effects. To identify the most influential predictors contributing to model performance, a response screening approach was applied. To fit the model, nonlinear least squares optimization was performed using the *optim()* function in R, with the L-BFGS-B algorithm applied to constrain parameter estimates within predefined bounds: Tb (0–15°C), To (10–35°C), and Tc (25–40°C). The optimization minimized the root mean square error (RMSE) between observed and predicted germination rates, and the coefficient of determination (R^2) was calculated to assess model fit. Predictive accuracy and the robustness of parameter estimates were further evaluated using 10-fold cross-validation implemented via the *createFolds()* function from the *caret* package, training each model on 90% of the data and validating it on the remaining 10%.

Results

Germination Response to Burial Duration, Seed Type, and Soil Moisture

Burial duration had the largest effect on winter wild oat (Figure 1). Soil water potential and

incubation temperature also exerted significant but secondary effects. Seed type significantly affected germination. Dehulled seeds exhibited higher CGF (Table 1) values (≈0.6) compared with intact seeds (≈0. 4).

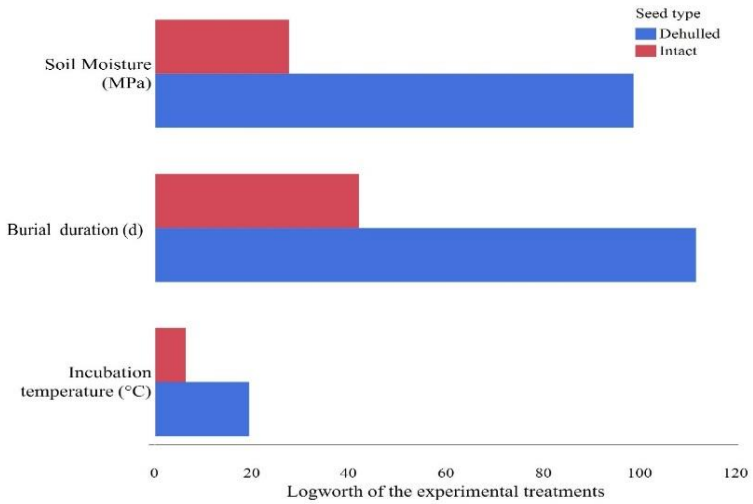

Figure 1. Comparison of experimental treatment contributions to the cumulative germination fraction of intact and dehulled *A. sterilis* subsp. *ludoviciana* seeds, based on log-worth values.

Table 1. Parameter estimates for the model predicting cumulative germination fractions

Parameter estimates	***Avena sterilis* subsp. *ludoviciana* (Dehulled)**	***Avena sterilis* subsp. *ludoviciana* (Intact)**
T_b	0/09	0/2
T_{o1}	15	12
T_{o2}	19	18
T_c	36	27
HA_{sub}	3/82	1/4
HA_{sup}	2/15	1/08

The relationship between CGF and burial duration followed a sigmoidal pattern for both seed types (Figure 2, left). The lack-of-fit test was not significant ($P > 0.6$), and all model parameters were significant ($P < 0.05$) with standard errors not exceeding 4% of the parameter values. Germination remained low during the first 60 days, increased sharply between 60 and 140 days, and reached a plateau thereafter. Dehulled seeds attained a maximum CGF of approximately 0.6, whereas intact seeds reached only ~0.1.

Soil water potential had a significant positive effect on cumulative germination fraction (CGF; Figure 2, right; $p < 0.05$), and parameter estimates were similarly significant ($p < 0.05$) with low standard errors (< 5%). Maximum germination occurred under high soil moisture (−0.03 to −0.4 MPa). At −0.8 MPa, germination was strongly inhibited for both seed types. Interaction effects between burial duration and soil water potential were significant, with higher CGF values under longer burial duration and higher soil moisture.

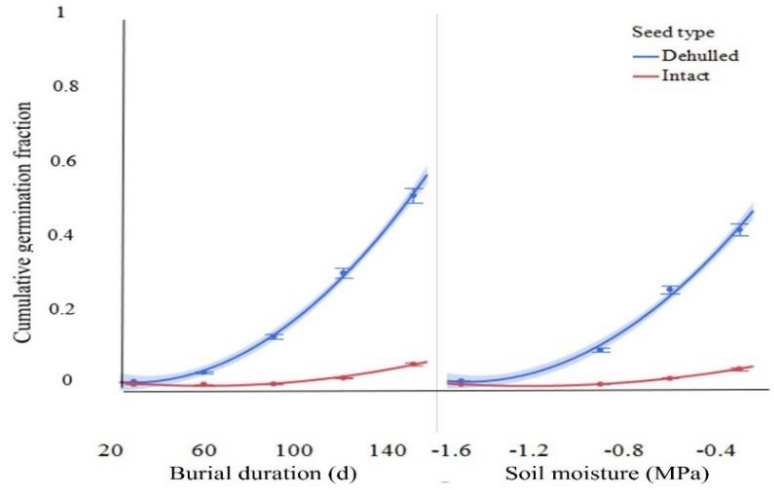

Figure 2. Comparison of experimental treatment contributions to the cumulative germination fraction of intact and dehulled *A. sterilis subsp. ludoviciana* seeds, based on log-worth values.

Thermal Time Accumulation

Thermal time (TT) accumulation, estimated using TAM, varied with incubation temperature (Figure 3). The TT accumulation increased from July to November. The highest TT and CGF values (≈0.6) were recorded at 15 °C, followed by 10 °C. At 25 °C and 30 °C, CGF values approached zero across all months. TT accumulation and CGF were lowest during July and August and highest during September to November.

Model Performance

Final model (Eq. 7) accurately predicted CGF across all treatments (Figure 4). The coefficient of determination (R^2) was 0.881, and the RMSE was 0.01. Observed and predicted CGF values showed a strong linear relationship, with data points closely aligned with the 1:1 line. Model residuals were randomly distributed across environmental gradients.

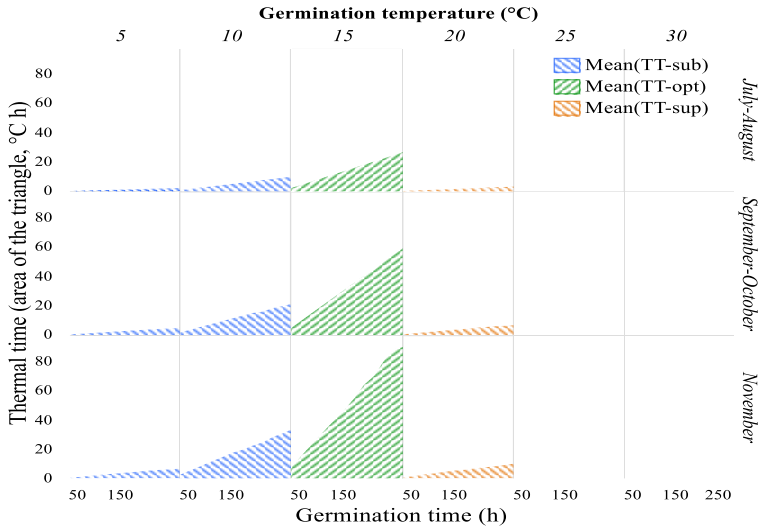

Figure 3. Thermal time (represented by the area of triangles) changes in different burial durations at different temperatures.

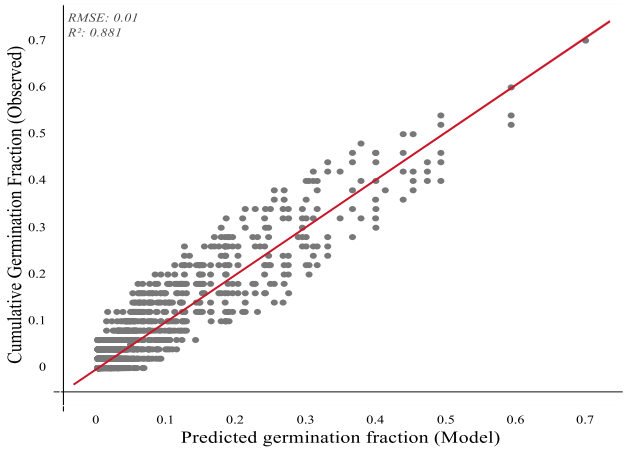

Figure 4. One-to-one line illustrates the agreement between the model predictions and the observed germination fraction for *A. sterilis* subsp. *ludoviciana* seeds.

Predicted Germination Dynamics Across Environmental Gradients

Model predictions (Figure 5) indicated the highest CGF values at burial duration exceeding 60 days, soil water potentials above −0.4 MPa, and temperatures between 10 °C and 15 °C. Under dry (−0.8 MPa) or extreme temperature conditions (≤ 5 °C or ≥ 30 °C), CGF values were close to zero. Dehulled seeds consistently showed higher predicted CGF values across all conditions.

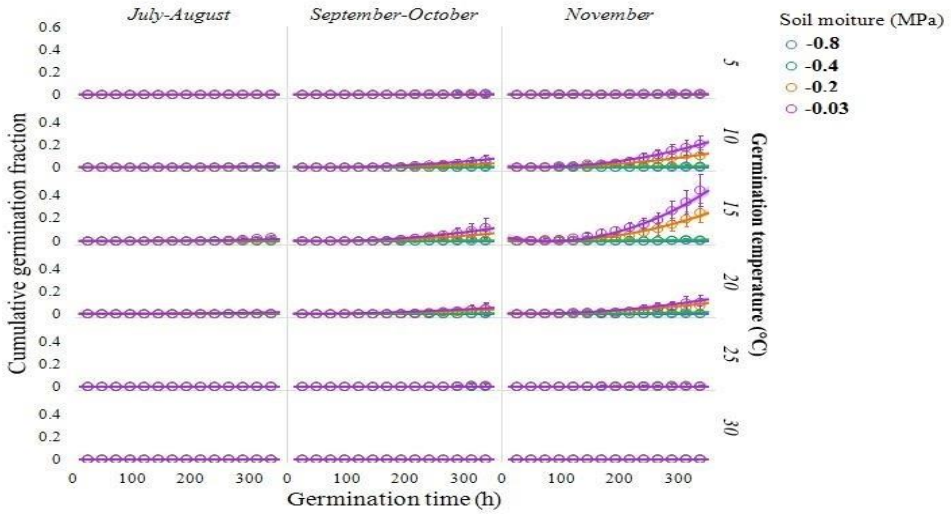

Figure 5. Predicting cumulative germination at different burial duration and different moisture potentials. Bars represent the standard error of the mean.

Discussion

Burial duration was identified as the dominant factor influencing the CGF of *A. sterilis* subsp. *ludoviciana* seeds, accounting for the greatest proportion of variance among treatments. This result aligns with Steinmaus et al. (2000), who demonstrated that dormancy release in *A. fatua* intensifies with extended burial due to physiological after-ripening processes. Similarly, Oveisi et al. (2025,b) reported that burial duration strongly governs germination potential and dormancy loss in related grass weeds, emphasizing that temporal exposure in the soil seed bank acts as the primary cue for germination readiness. The strong response to burial duration observed here underscores the role of time-dependent physiological transitions, such as changes in abscisic acid

sensitivity, hormonal balance, and membrane integrity, in regulating dormancy release.

Temperature and soil moisture exerted secondary but significant influences, shaping germination dynamics once dormancy was reduced. Bradford (2002) noted that suboptimal hydrothermal conditions limit the activation of metabolism in grass seeds, while Hu et al. (2018) observed that both temperature and water potential interact to define the boundaries of the germination niche. Our findings are consistent with these studies: moderate temperatures and adequate soil moisture promoted germination, but their effects were less pronounced than that of burial duration, suggesting that environmental factors mainly modulate germination after dormancy has been physiologically alleviated (Klupczynska & Pawłowski, 2021).

Seed type introduced an additional dimension to germination variability. Dehulled seeds germinated faster and reached higher CGF values than intact, hulled seeds. This pattern supports the findings of Baskin and Baskin (2000) and Lamont and Pausas (2023), who identified the hull as a physical constraint that limits water uptake and oxygen diffusion. The removal of the hull likely eliminates mechanical and permeability barriers, facilitating more rapid hydration and metabolic activation. Consequently, dehulled seeds exhibit greater sensitivity to favorable environmental cues, while intact seeds retain delayed or reduced germination, enhancing bet-hedging and seed-bank persistence.

The CGF–time relationship exhibited a clear sigmoidal trend for both seed types. An initial lag phase (0–60 days) with minimal germination was followed by a sharp increase between 60 and 140 days, then a plateau or slight decline beyond 140 days. Comparable sigmoidal responses in *A.* species have been described by Benech-Arnold et al. (2000) and Ukalska and Jastrzebowski (2019), reflecting dormancy cycling under burial condition. The eventual stabilization or decline in CGF likely reflects loss of seed viability, as also noted by Probert (2000). Soil water potential further modulated this trajectory: maximum germination occurred under moderate moisture (−0.03 to −0.6 MPa), conditions favorable for imbibition and enzymatic activity (Pires et al., 2017). At −1.2 MPa, CGF approached zero, confirming the strong inhibitory effect of water stress on germination (Finch-Savage & Leubner-Metzger, 2006). Intact seeds were especially sensitive to desiccation, consistent with Foroozesh et al. (2018), who reported that the hull amplifies drought effects by further restricting moisture absorption. Overall, dormancy release in *A. sterilis* subsp. *ludoviciana* appears primarily time-dependent, with hydrothermal conditions modulating expression, and seed morphology influencing sensitivity to stress.

Thermal time (TT) accumulation analysis provided further insight into temperature-dependent germination behavior. TT accumulation increased from July to November, reflecting progressive alignment between environmental temperatures and the thermal optimum for germination. Our finding corroborates the work of Garcia-Huidobro et al. (1985), who defined a similar thermal optimum for *A. fatua*, and Chen et al. (2021), who found that germination rate is maximized under cool, mid-autumn temperatures typical of the species' natural emergence period. A secondary peak at 10 °C further suggests a broad optimal range, allowing germination flexibility under variable late-autumn conditions. At higher temperatures (25–30 °C), TT accumulation and CGF were negligible, indicating heat inhibition of germination. Covell et al. (1986) attributed such suppression in oats to thermal disruption of enzyme activity and respiratory balance, while Valickova et al. (2017) observed similar reductions in germination efficiency beyond the supra-optimal threshold. Seasonal patterns in TT accumulation, low in midsummer (July–August) and high in autumn (September–November), mirror natural germination timing in Mediterranean and temperate agroecosystems, suggesting strong ecological

adaptation to cooler seasonal niches. These results indicate that *A. sterilis* subsp. *ludoviciana* germination is closely regulated by accumulated thermal exposure, reinforcing its classification as a winter-annual species adapted to autumn establishment.

Model predictions highlighted the combined influence of burial duration, moisture, and temperature on germination dynamics. Extended burial, moderate soil water potentials, and cool temperatures jointly maximized CGF, reaching up to 0.6 by November. These conditions correspond to late-autumn field environments when soil moisture is replenished and temperatures decline—factors known to promote wild oat emergence (Steadman et al., 2003; Scherner et al., 2017). Conversely, early-season conditions characterized by high temperature (≥ 25 °C) or severe water deficit (≤ −1.2 MPa) suppressed germination, consistent with the thermal and hydric thresholds described by Zhou et al. (2005). This seasonal asymmetry reinforces the species' adaptive strategy: delaying germination until post-summer cooling ensures that emerging seedlings coincide with optimal growth conditions and reduced desiccation risk.

Across environmental gradients, dehulled seeds consistently exhibited higher CGF than intact seeds, confirming that the hull imposes additional resistance even under favorable conditions. Tang et al. (2022) and Baskin and Baskin (2000) similarly reported that seed coverings can maintain a portion of the population in a dormant state, promoting temporal dispersal of emergence events. Such heterogeneity enhances population persistence by buffering against environmental unpredictability, a hallmark of successful weed strategies in annual cropping systems.

Conclusions

Collectively, these findings show that germination in *A. sterilis* subsp. *ludoviciana* is governed primarily by burial duration, with additional regulation by soil moisture and temperature. The developed TAM successfully described germination responses across these interacting factors, indicating that prolonged burial under adequate moisture promotes dormancy release, whereas severe drought suppresses germination and likely contributes to dormancy maintenance. These results further suggest that summer drought, lack of irrigation, and summer fallow conditions may delay winter wild oat emergence. Under ongoing climate change, such shifts in soil moisture regimes may not only alter the timing and magnitude of emergence flushes, but may also favor the persistence or selection of more drought-tolerant weed populations, with important implications for weed management in arid and semi-arid cropping systems.

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