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Climate effect on *Avena fatua* field emergence dynamics: a 38-year experiment in the Semiarid Pampean Region of Argentina

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Abstract

Climate events modulate weed population dynamics mainly by influencing field seedling emergence patterns. Field experiments aiming to study the influence of climate on the early-stage establishment of weeds are of utmost importance from a practical and strategic decision-making management point of view. The objective of this work was to analyse the effect of climate variations on the field emergence dynamics of *Avena fatua* in the southwest area of the semiarid Pampean region of Argentina. Field emergence patterns of *A. fatua* were monitored from 1977–2015. Seedling counts were destructively sampled at weekly intervals. Three quadrats (1 m² each) were randomly distributed on a 5 ha experimental field with a high natural population density of *A. fatua* in the absence of a crop. Results show that the emergence strategy of this species is highly plastic with a striking variation in response to year-to-year climate signals. *Avena fatua* field emergence strategies were classified as staggered, early, medium and late based on both chronological and hydrothermal-time parameters. In the short-term, precipitation regimes during both the after-ripening and

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emergence phases largely explained the resulting emergence strategy. In the long-term, the combined effect of a reduction in both the precipitation frequency and the mean minimum temperature correlated with an increase in the staggered emergence pattern. Results also point out the adaptability of *A. fatua* in the area under study, further suggesting a bet-hedging fitness strategy that could diminish the risk of population decline under changing climate scenarios. From an agronomic perspective, the occurrence of staggered emergence patterns with an extended emergence window would complicate the definition of the optimal time for weed control. Thus, tailoring decisions based on the Southern Oscillation Index (SOI) episodes (neutral, negative or positive) forecast plus the implementation of weed emergence models could lead to more accurate and sustainable weed management decisions.

Keywords

Climate change, Southern Oscillation Index, AVEFA, seed dormancy, maternal effect, after-ripening, weed management.

1 | Introduction

Climate events influence ecophysiological cues affecting vegetation dynamics (League & Veblen, 2006; Baeten et al., 2010). As reviewed by Walck et al (2011), climate variations have a major effect on the early stages of plant development thus influencing seedling recruitment. Among the most important global-scale climate events, the Southern Oscillation Index (SOI) which occurs across the tropical Pacific Ocean is characterized by variations in the temperature of the surface of the eastern Pacific Ocean and the air surface pressure in the tropical western Pacific. The warm oceanic episode (El Niño) accompanies high air surface pressure while the cold episode (La Niña) accompanies low air surface pressure (Stone et al., 1996; Monzon et al., 2012).

The impact of climate events on weed population dynamics and specifically on field emergence is of utmost importance from both an ecophysiological knowledge-based perspective as well as from an optimal weed management strategic point of view. As indicated by Royo-Esnal et al. (2020), a precise characterization of weed species field emergence dynamics has two main objectives: (1) understanding seedling emergence allows

us to better comprehend the weed population dynamics, and the capacity for competition with the crop; (2) optimising control - as early growth stages show the highest susceptibility to control interventions.

Climate variations are expected to influence weed seed dormancy and germination which directly impact field emergence dynamics. Seed dormancy is one of the most important attributes of weed seedbanks defining both the rate and magnitude of seedling emergence (Benech-Arnold et al., 2000). Soil temperature is widely acknowledged as the main regulatory variable of seed dormancy which is also modulated by soil water content in many cases. Seedbank dormancy levels are defined by seasonal soil temperature fluctuations which define the amplitude of the permissive germination range of a given weed population (Batlla et al., 2020). For summer annual weed species, dormancy release occurs after seed stratification during winter resulting in low dormancy levels at the beginning of spring. Conversely, winter annuals are released from dormancy by seed after-ripening during late spring and summer. For winter annual species, an increase in temperature during the after-ripening phase associated with climate events (warming effects) are expected to increase the rate of seed dormancy release. The distribution of autumn rains is also expected to influence both the timing and magnitude of field germination once dormancy release requirements are fulfilled (Walck et al., 2011).

Wild oat (*Avena fatua* L.) is one of the most conspicuous weeds of the world causing considerable yield and quality losses in cereal crops (Scursoni et al., 2011; Matsushashi et al., 2021). *Avena fatua* is a facultative winter annual species meaning that emergence occurs mainly in autumn and to a lesser extent during early spring. However, a highly plastic field emergence response has been observed under different climate regions worldwide. For example, in temperate environments with mild winters and non-severe soil moisture limitations, field emergence dynamics follow a regular sigmoidal-type pattern within a relatively short emergence window (Page et al., 2006; Martinson et al., 2007; Chantre et al., 2014). Conversely, under semi-arid temperate conditions, *A. fatua* displays irregular time-distributed cohorts (Chantre et al., 2012, 2018; Blanco et al., 2014; Molinari et al., 2020). Such ecophysiological behaviour suggests that *A. fatua* might have developed specific adaptations to different climate conditions (Chantre et al., 2014) which could be modulated, at least to some extent, by the duration of primary seed dormancy.

Maternal effects associated with environmental heterogeneity during seed formation and maturing are expected to influence seed dormancy. High field temperatures during seed development have been shown to increase germinability of recently harvested seeds of *A. fatua* (Sawhney & Naylor, 1980; Peters, 1982) and other facultative winter annual species, such as *Buglossoides arvensis* (Longas et al., 2016). Besides, seeds produced by water-stressed plants of *A. fatua* exhibited a shorter duration of primary dormancy (Sawhney and Naylor, 1982). Seed dormancy levels could also be influenced by the diversity of genetic adaptations in natural populations of *A. fatua* (Jana & Naylor, 1980; Adkins et al., 1986; Fennimore et al., 1999) as well as genotype-environment interactions which play an adaptive role on ecosystems' colonization (Naylor & Fedec, 1978). Therefore, maternal effects associated with large inter-annual rainfall variability and seasonal temperature fluctuations, such as those typically registered in the semiarid Pampean region of Argentina, are expected to influence *A. fatua* seed dormancy levels which could further impact field emergence dynamics.

Many aspects of agricultural production are related to the SOI in the Argentinian Pampas and other cropping regions of the globe (Podesta et al., 2002; Bert et al., 2006; Monzon et al., 2007; Zhang et al., 2008). Forecasts of crop yield, such as corn, sorghum, and wheat, have been made based on SOI episodes (de la Casa & Ovando, 2006; Monzon et al., 2007; Iizumi et al., 2014). In the same way, SOI episodes have been used to set the termination date of cover crops before corn sowing to prioritize the soil water reserve in relation to biomass accumulation of the cover crop (Renzi & Cantamutto, 2013). Despite this fact, the current knowledge on the impact of the SOI on weed population dynamics, and particularly on field emergence dynamics, is very scarce.

Based on these statements, we hypothesize that climate events influence both the frequency and magnitude of the field emergence patterns of *A. fatua* in the semiarid Pampean region of Argentina. Specifically, a highly variable environment is expected to favour a bet-hedging strategy, allowing emergence in a wider range of conditions, to reduce the risk of population decline. The objectives of our work were to i) evaluate inter-annual climate fluctuations on *A. fatua* field emergence patterns, and ii) explore relationships among climate conditions associated with the SOI and the registered field emergence patterns. Climate effects were

studied through a 38-year experiment performed in the southwest area of the semiarid Pampean region of Argentina (Bordenave, Buenos Aires, Argentina).

2 | Material and Methods

2.1 | Field experiment

Avena fatua field emergence data were collected at weekly intervals during 38 years (1977-2015) at the EEA INTA Bordenave (37°46'08.0"S 63°05'30.5"W), located in Buenos Aires province, Argentina. The experiment was conducted on an undisturbed field with a high natural population density of *A. fatua* without crop presence.

Seedling counts were performed at weekly intervals on three quadrats (1 m² each) randomly distributed in the field. A destructive method was implemented to avoid coexistent vegetation that could have influenced *A. fatua* emergence dynamics. At the end of each year of experimentation (corresponding to mid-summer = 31 December for the southern hemisphere), the quadrats were removed and newly distributed at random into the remaining area of the 5 ha experimental field. This way, the seedbank of a particular year was not affected by the elimination of seedlings during the counting process of the previous years.

2.2 | Climate data collection and analysis

Climate data were obtained each year from a meteorological station located within the experimental field of EEA INTA Bordenave (1976–2015). Data were separated to account for climate effect on (i) seed formation/maturing in the mother plants (i.e. maternal effects) and field after-ripening period (hereafter ‘after-ripening phase’, AR); (ii) the germination and seedling emergence period (hereafter ‘emergence phase’, E) of *A. fatua*. To discriminate maternal from germination environmental effects, we assumed that the after-ripening phase extended from mid-spring till mid-summer (October-till-January), while the emergence phase encompasses mid-summer till mid-late spring (February-till-November). The emergence phase was also divided into autumn (February-till-April), winter (May-till-August) and spring period (September-till-November). Such distinction between phases was based on both experimental and simulated data generated by Molinari et al. (2020).

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For data analyses, daily temperature (minimum, mean and maximum) and both the frequency and amount of total precipitation (mm and n° of rain events) for each phase and period in each year were used. The daily thermal amplitude (DTA) was calculated as the difference between the maximum and minimum temperature per day. The occurrence of extremely high temperatures during both phases was quantified using heat-stress units. Heat stress units (HSU) were the sum of the daily maximum temperature above >30°C, calculated following Teasdale & Cavigelli (2017):

$$HSU = \sum_{i=1,n} (T \max_i - 30^{\circ}C)$$

2.3 | Hydrothermal-time (HTT) estimation using soil microclimate data

The Soil Temperature and Moisture Model (STM²) developed by USDA-ARS was used to estimate soil microclimate conditions (Spokas & Forcella, 2009). STM² estimates soil temperature and moisture data based on soil composition and daily minimum and maximum air temperature and precipitation. For the region under study, STM² outcomes were successfully validated by Damiano et al. (2010) and Renzi et al. (2019). STM² was calibrated using soil site-specific parameters: soil texture (sandy loam = 53% sand, 31% silt, 16% clay), OM content (3.1%) and bulk density (1.2 Mg m⁻³). Both OM content and bulk density were monitored every 3 years. The presented values remained unaltered during the experiment.

Daily mean soil temperature (T) and water potential (Ψ) were estimated using weather data registered at a meteorological station located in the same experimental field. Hydrothermal-time was calculated following Bradford (2002):

$$\theta_{HTT_n} = \sum_{i=1,n} \theta_i H_i \quad (1)$$

where

$$\theta_i = \begin{cases} T_i - T_b & \text{if } T_i > T_b \\ 0 & \text{otherwise} \end{cases}$$

$$H_i = \begin{cases} 1 & \text{if } \Psi_i > \Psi_b \\ 0 & \text{otherwise} \end{cases}$$

T_i is the estimated mean daily soil temperature; T_b is the base temperature for seedling emergence; Ψ_i is the daily soil water potential and Ψ_b is the base water potential for seedling emergence. $T_b = 1^\circ\text{C}$ (Cousens et al., 1992) and $\Psi_b = -1.2 \text{ MPa}$ (Page et al., 2004). Hydrothermal-time ($\text{MPa}^\circ\text{Cd}$) accumulation start on 1 February 1.

Previous studies suggest that for non-tillage systems seed are between 0–5 cm (Ghersa & Martinez-Ghersa, 2000). In this study, we have decided to use 5 cm to estimate both temperature and soil water potential profiles. This is an open discussion and some work have been devoted to optimal depth determination, see Cao et al. (2011).

2.4 | Seedling emergence traits

Several traits were used to characterise the seedling emergence dynamics of *A. fatua* from 1977-2015. The following features were calculated: i) Days_{10} , Days_{50} and Days_{90} which represent the chronological time required to reach 10, 50 and 90% of cumulative emergence from the onset of the emergence phase (1 February = zero emergence time); ii) the emergence window (EW) calculated as $[\text{Days}_{90} - \text{Days}_{10}]$; iii) HTT_{10} , HTT_{50} and HTT_{90} which represent the hydrothermal-time ($\text{MPa}^\circ\text{Cd}$) required to reach 10, 50 and 90% of emergence; and iv) EW (HTT) which stands for the amount of hydrothermal-time accumulated from 10 to 90%, calculated as $[\text{HTT}_{90} - \text{HTT}_{10}]$. For each year, eight traits that characterized the pattern of seedling emergence were obtained (Table S4).

2.5 | Data analysis

Pearson correlation coefficients were calculated between seedling emergence traits by InfoStat software (Di Rienzo et al., 2013). Four clusters were defined from the seedling emergence traits. For cluster analysis, a matrix based on Euclidean distance was computed and agglomeration was performed using Ward's minimum-variance linkage using Infostat software. To define the four clusters, the cut line was used at a distance equal to 50% of the maximum distance.

Then, it was defined if there were differences between clusters in the seedling emergence traits, and among climate variables defined in the after-ripening and emergence periods per

each cluster. To determine if the differences between clusters could be explained by the climate variables in either the after-ripening or emergence periods, a linear mixed model (LMM) was performed (Table S4). The LMM was performed using the cluster as a fixed factor and years as a random factor. The LMM was performed with R version 3.6.3 (R Development Core Team, 2019) using Infostat software interface to R. Clusters were compared by Fisher's Least Significant Difference test ($P < 0.05$).

Relationships between climate variables and the Southern Oscillation Index (SOI) were investigated. The SOI is a measure that can be used in developing a seasonal forecasts system. The SOI measures the difference in surface air pressure in the central and eastern sector of the tropical Pacific Ocean and is defined as a departure from average or "anomaly" centred in 30-year base periods. SOI data based on a threshold of $\pm 0.5^{\circ}\text{C}$ were used to divide the after-ripening and emergence phases of each year into warm, cold and neutral episodes (commonly identified as "Niño", "Niña" and "Neutral"). The SOI is moderately correlated with future seasonal rainfall in some regions (Stone et al., 1996; Iizumi et al., 2014). The Climate Prediction Centre (CPC; www.cpc.ncep.noaa.gov) keeps an online record of all the seasonal temperature anomalies back to 1950 (L'Heureux et al., 2013). A LMM was performed to test the degree that the climate variables differed as a result of the SOI episodes, in both the after-ripening and emergence phases.

Linear regression analyses among precipitation or mean minimum temperature from 1977 to 2015 were performed using GraphPad Prism Software version 6.0 (GraphPad, San Diego, California, USA). Clusters evolution frequency from 1976–2015 were analysed by a nonlinear regression procedure. The goodness of fit was determined by calculating the residual-mean-square error (RMSE) (Mayer & Butler, 1993).

3 | Results

3.1 | Inter-annual climate effect on field emergence traits

Climate variables exhibited a wide range of inter-annual variability mainly regarding the frequency and total precipitation as well as in the sum of heat-stress units (Table S1, supplementary material online). Also, high variability was observed between years for the emergence traits (Table S2). Among the latter, 75% were moderately correlated, except for

Days₉₀ and HTT₉₀ which were associated with 28% and 43% of the traits respectively (Table S3).

Four emergence patterns were identified via cluster analysis (Fig. 1) and further classified as staggered (Cluster 1), early (Cluster 2), medium (Cluster 3) and late (Cluster 4) emergence. As observed in Table 1, the onset of emergence varied from late summer (i.e. staggered and early emergence patterns) to late autumn (i.e. late emergence). Clusters 1 and 2 showed lower values of HTT and chronological time to reach 10% cumulative emergence. HTT₅₀ values were 1.6-fold higher on average for medium and late dynamics compared to the staggered and the early emergence strategy. The latter strategy also showed the minimum average time to 50% cumulative emergence (Table 1). The extent of the emergence window was significantly lower for the late pattern when compared to the rest of the clusters showing a 60% reduction on the average hydrothermal-time requirement (see EW (HTT), Table 1).

Significant differences were observed between clusters when the different climate variables were depicted according to the after-ripening and emergence phases (Table 2).

The staggered emergence pattern was associated with the lowest precipitation records during both the after-ripening and emergence phases. As indicated in Table 2, a significant reduction in the number of precipitation events was registered during both phases for the same strategy. Besides, the lowest values of total amount of precipitation and mean minimum temperature during the field emergence phase corresponded to the staggered strategy (Table 2). Conversely, late patterns were characterised by the maximum amount of precipitation during the seed formation and maturing of *A. fatua* seeds. As indicated in Table 2, for the late strategy, the amount of precipitation was 1.8-fold higher during seed formation/maturing in the field compared to the average value of the remaining strategies.

No significant differences were observed among *A. fatua* emergence strategies concerning mean temperature values during both phases (Table 2). However, a negative relationship between heat-stress units and Days₁₀ and HTT₁₀ was observed ($r^2 = 0.96$ and 0.98 ; $P < 0.05$; Figure S1). Thus, an increment in heat-stress sum (°Cd) during the after-ripening phase reduced both the number of days and the hydrothermal-time required for the onset of field emergence favouring a staggered or early emergence behaviour.

3.2 | Southern Oscillation Index (SOI) patterns

Southern oscillation index (SOI) values from 1976 to 2015 for both the after-ripening and emergence phases are presented in Fig S2a. The frequency of warm, neutral and cold episodes for the SOI are presented by decade (Fig. S2b).

Fig. 2 shows the significant relationships obtained from the LMM relating SOI episodes to climate variables in both the emergence and after-ripening phases. As indicated in Fig 2, SOI behaviour was related to precipitation distribution during both bioecological phases, and also to the mean minimum temperature and the daily thermal amplitude during the emergence phase. Compared to the warm episode, both cold and neutral SOI episodes were associated with a reduction in the frequency of precipitation during seed development in the mother plants (Fig 2a). During the emergence phase, lower mean minimum temperature (Fig. 2b) and lower precipitation (mainly in winter, Fig. 2c), as well as an increment on the daily thermal amplitude (Fig. 2d) were registered. No differences were observed among SOI episodes for the remaining climate variables.

3.3 | Long-term trends on climate variables and emergence traits

Regression analysis indicates a significant reduction in both precipitation frequency (Fig. 3a) and minimum mean temperature (Fig. 3b) for both the after-ripening and emergence phases from 1977 to 2015. By comparing the accumulated frequency per cluster means, we observed an exponential increment of the staggered strategy from 1977 to 2015 (Fig. 3c). In addition, during the last decade, the highest rate of increment of the accumulated frequency also corresponds to the staggered strategy.

4 | Discussion

Temperature, precipitation and other climate variables influence intraspecific variation in the germination strategy of some species. This has been typically tested among populations from different environmental origins (Donohue et al., 2010, 2013; Lampei et al., 2017; Barga et al., 2017; Hradilová et al., 2019; Renzi et al., 2020b).

In this contribution, we analysed the effect of climate variations on the field emergence dynamics of *A. fatua* using a long-term field experiment. Field emergence patterns were monitored during 38 years (1977–2015) in the semiarid Pampean region of Argentina. The

analysis of the effect of climate variations for a given site and weed population (i.e. genotype) for such a long-time span turns this contribution into a valuable and almost unique study case.

Among the potential limitations of this study, we should mention that an unambiguous distinction among maternal, after-ripening, germination and post-germination environmental effects is lacking. Based on both experimental and simulated data obtained from Molinari et al. (2020), we assumed a rather simplified temporal distinction between the ‘maternal/after-ripening phase’ and the ‘germination/emergence phase’ to analyse climate variations on the field emergence dynamics. Also, we assumed that the majority of the new seedlings in a given year results from seed dispersal of the previous year. Despite the short-term persistent character of the seedbank (Scursoni et al., 2001), the latter assumption is partially correct, as older seeds might also contribute to new seedling recruitment.

Considering both strengths and limitations of this work, our results indicate a striking variation among years in the emergence strategy of *A. fatua*. Four emergence strategies were identified and classified as staggered, early, medium and late. In the present study, precipitation regimes during both the after-ripening and emergence phases largely explained the resulting field emergence strategy of *A. fatua*. During the emergence phase, a lower precipitation regime could be associated with a lower mean minimum temperature and the increment of the daily thermal amplitude (Table 2).

As stated by Renzi et al. (2020a), patterns of field emergence may reflect species local adaptations. From our perspective, the local adaptation of *A. fatua* is evidenced by a highly plastic response represented by a large inter-annual variation of the emergence patterns. Recently, de Souza Vidigal et al. (2020) observed that seed dormancy in *Arabidopsis thaliana* was largely controlled by the environment more than the genotype. In our study, the resulting emergence strategy of *A. fatua* was mainly determined by precipitation during both the after-ripening and emergence periods.

Thus, weed emergence prediction models based on short-term data under highly variable environments could lead to erroneous estimations of field emergence (Chantre et al., 2018). Other works have also shown that the accuracy of seedling emergence models in *Lolium rigidum* and *Avena sterilis* varied from site to site, with better performance under humid locations compared to very dry climate conditions (Sousa-Ortega et al., 2020, 2021).

In the semiarid region under study, dry climate conditions during both the after-ripening and emergence phase increased the emergence window suggesting that a staggered pattern could indicate a plant bet-hedging strategy, which distributes seedling emergence timing across the growing season, either growing faster as autumn seedlings or germinating in safer spring conditions (Simons, 2014). Bet-hedging could enhance population fitness being a valuable strategy to deal with environmental unpredictability at a local scale (Cohen, 1966; Venable, 2007; Satyanti et al., 2019; Gianella et al., 2021). Barga et al. (2017) working with arid land species showed that a higher variation in the annual precipitation regime turns into a bet-hedging germination strategy, thus seeds are capable of germinating in response to low-amount precipitation events rather than waiting for optimal thermal and soil moisture conditions to occur. From a practical viewpoint, a wide emergence window would complicate the definition of the optimal intervention tactic, such as delayed crop sowing, tillage or herbicide application time (Cirujeda & Taberner, 2009; Royo-Esnal et al., 2020).

The late strategy was related to a high precipitation regime during both the after-ripening and emergence phases and low rainfall events during winter (Table 2). Precipitation during winter might be the determinant factor to trigger early field emergence. However, it is plausible that early germination on the late strategy could also be constrained by physiological seed dormancy. Sawhney & Naylor (1982) showed that seeds of *A. fatua* matured under adequate soil moisture levels exhibited a longer duration of innate dormancy compared to seeds produced by water-stressed plants. Recently, field studies performed with *Lolium multiflorum* showed that higher temperature and lower precipitation during seed development were correlated with lower innate physiological dormancy (Fernández et al., 2021).

Temperature variability is also an important factor in the regulation of seed dormancy (Sawhney and Naylor, 1979). However, our results indicate that the thermal variability among years was low (< 7% CV, Table 1S) not showing a significant effect on the emergence pattern (> 30% CV). Although differences between the emergence strategy and temperature were not significant, a significant negative response between heat-stress units (HSU) and days (Days_{10}) or hydrothermal-time to reach 10% of emergence (HTT_{10}) was observed. Seeds developed on the mother plants at warmer temperatures (high HSU) are less dormant at

maturity (Fenner, 1991; Fernández et al., 2021), and this could be associated with earlier germination.

The ecological implication of different emergence strategies between years could play a significant role under changing climate scenarios, particularly in semiarid and arid regions. Early plant life state is crucial to better understand species response to climate change (Satyanti et al., 2019). Our results suggest that in the long-term, a combined reduction of the precipitation frequency during both the after-ripening and emergence phases as well in the mean minimum temperature would increase the occurrence of the staggered emergence strategy in *A. fatua*. Therefore, climate trends point out the adaptability of *A. fatua* to cope with both long-term precipitation and temperature changes, further suggesting bet-hedging as an enhanced fitness strategy. As indicated by our results, also cyclic SOI events produce an effect on *A. fatua* emergence patterns. For instance, cold episode events associated with a lower frequency of precipitation events as well as lower temperatures (Fig. 2) increased the occurrence of the staggered emergence strategy.

The SOI episodes could be used to quantify future precipitation probabilities in the semiarid Pampean region of Argentina, reducing the potential risk of “bad” years not only on the impact of crop yield but also on the weed management strategy (Stone et al., 1996; Monzon et al., 2012; Iizumi et al., 2014). The selection of the crop type according to the SOI episodes with some months of advanced warning, and the adjustment of the crop sowing date plus conventional or alternative weed control methods based on emergence prediction models could improve long-term weed management strategies. During warm episode events, sowing of cereal crops and the use of regular sigmoidal-type pattern emergence models with a relatively short emergence window could ease the definition of the optimal intervention time from a decision-making perspective. Conversely, if cold episode events occur, a more complex decision-making scenario would demand the selection of highly competitive cereal cultivars, increasing sowing densities as well as the use of more flexible emergence prediction models (Chantre et al., 2018). These points suggest that different models may be necessary to accurately predict *A. fatua* under different SOI episodes. This conclusion could be extended to other facultative winter annual weed species under semiarid and arid environments.

In conclusion, we have demonstrated a substantial within-population variation in the field emergence strategy of *A. fatua* which correlates with climate drivers in the short and long-term time scales.

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Conflicts of interest

None.

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Figure captions

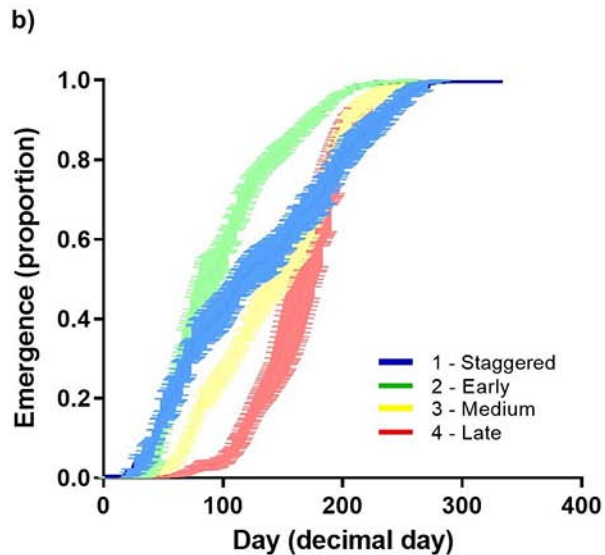
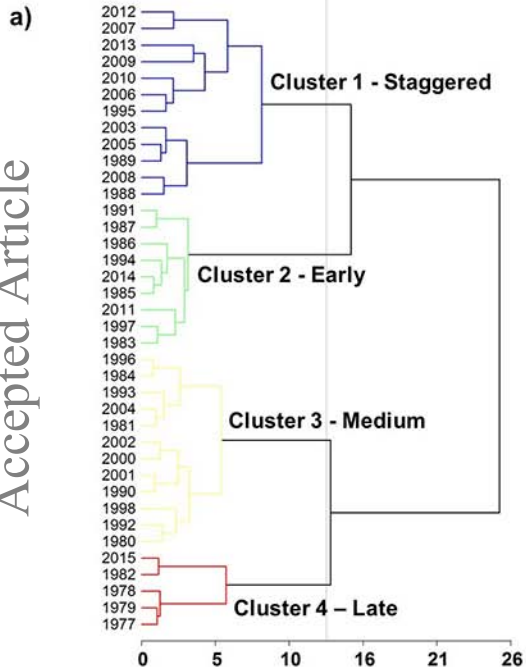
Figure 1. Clustering of *Avena fatua* field emergence data (1977-2015) per year based on chronological time and hydrothermal-time (HTT) to reach 10, 50 and 90% of cumulative emergence and the corresponding ‘emergence windows’ resulting from [90–10]. HTT and Julian days accumulation start on 1 February (=zero emergence time). Euclidean distance and Ward’s minimum-variance linkage hierarchical method (a), and (b) field emergence patterns as a function of chronological time (mean \pm standard error) are shown.

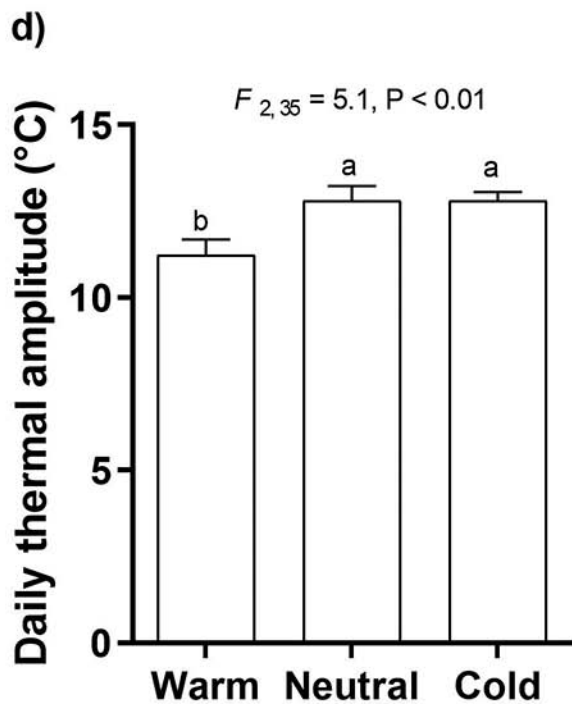
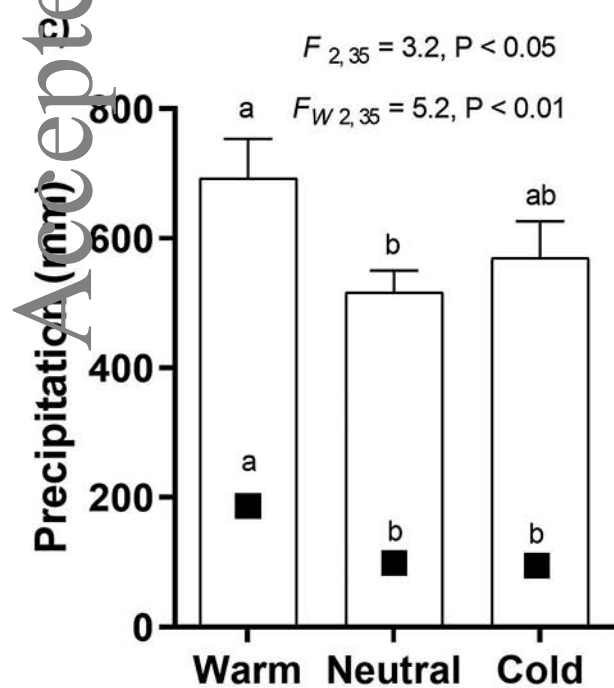
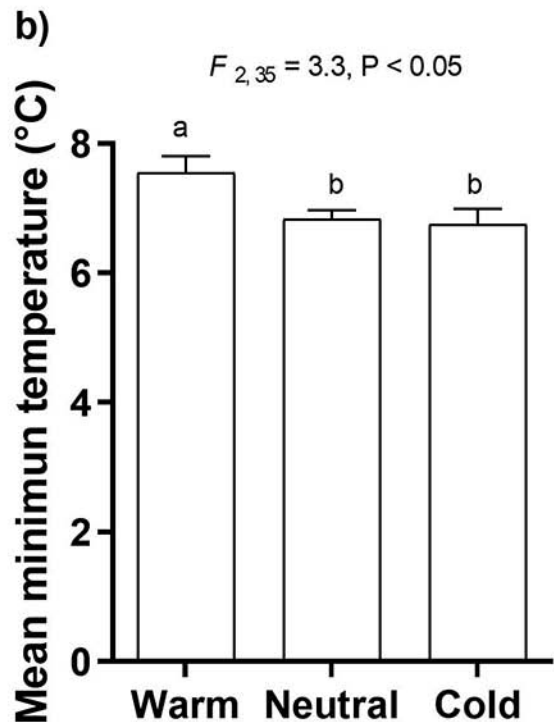
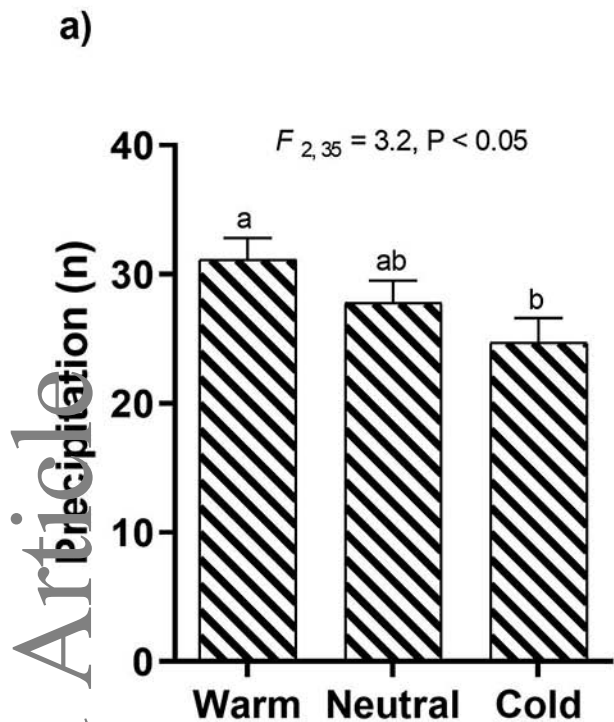
Figure 2. Warm, neutral and cold episodes related to precipitation frequency (n of events) during after-ripening phase (AR) (a). Mean minimum temperature (b), precipitation amount (mm) (c), and daily thermal amplitude are shown for emergence phase (E). Black squares in (c) show winter precipitation.

Figure 3. Precipitation (a), mean minimum temperature (b) accumulated frequency per cluster (c) from 1977 to 2015.

Figure S1. Relationship between heat-stress units (HSU) and chronological time (Days₁₀) and hydrothermal-time (HTT₁₀) to reach 10% of cumulative emergence during AR phase (seed formation/maturing and after-ripening). Bars indicate \pm standard error (SE). The numbers 1-to-4 indicate staggered, early, medium and late patterns, respectively.

Figure S2. Southern oscillation index (SOI) from 1976 to 2015 depicting after-ripening phase (AR) (i.e. seed formation/maturing and after-ripening) and emergence phase (E) (i.e. germination and seedling emergence) (a), and percentage of episodes (AR+E) per decade (b). The warm (Niño) and cold (Niña) range were based on a threshold of $\pm 0.5^\circ\text{C}$ for the SOI.





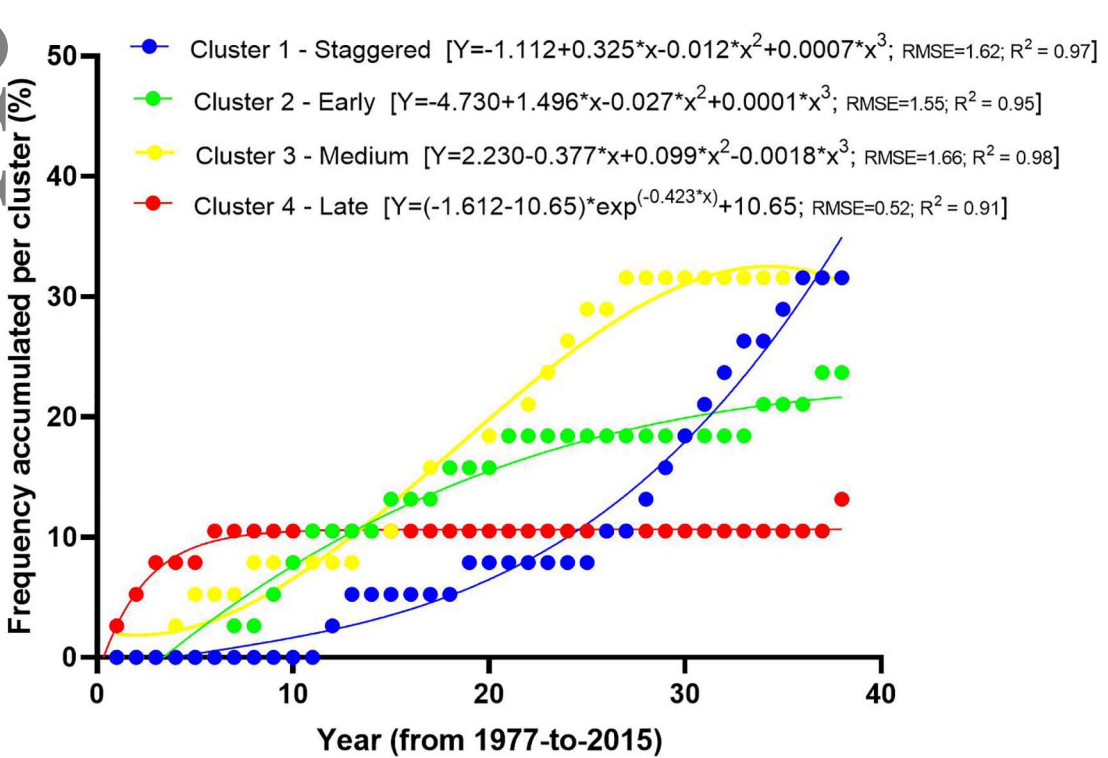
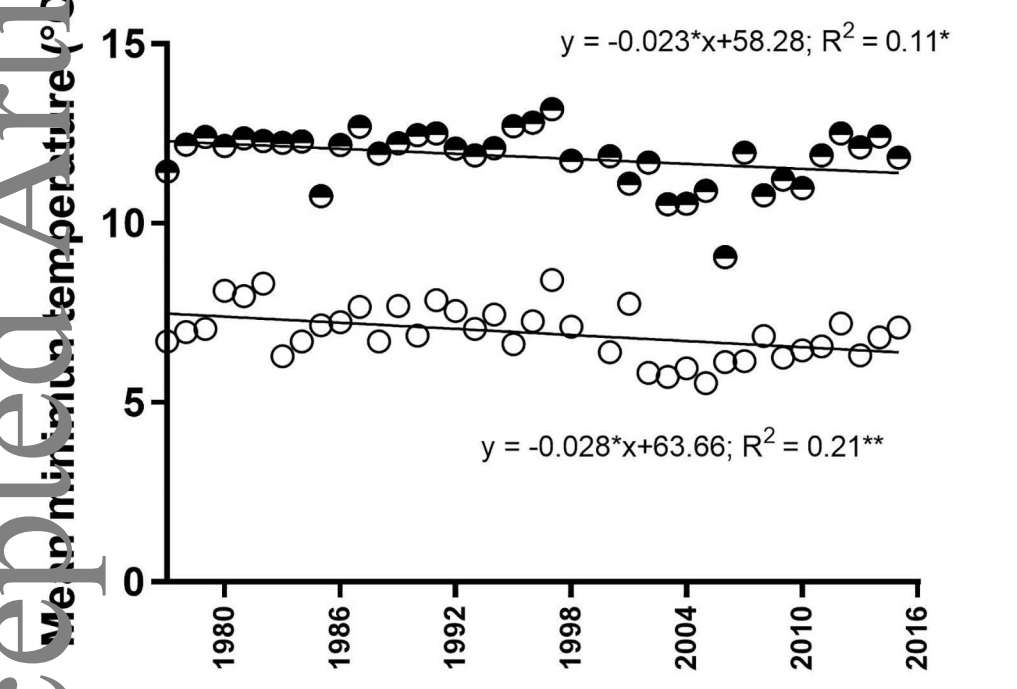
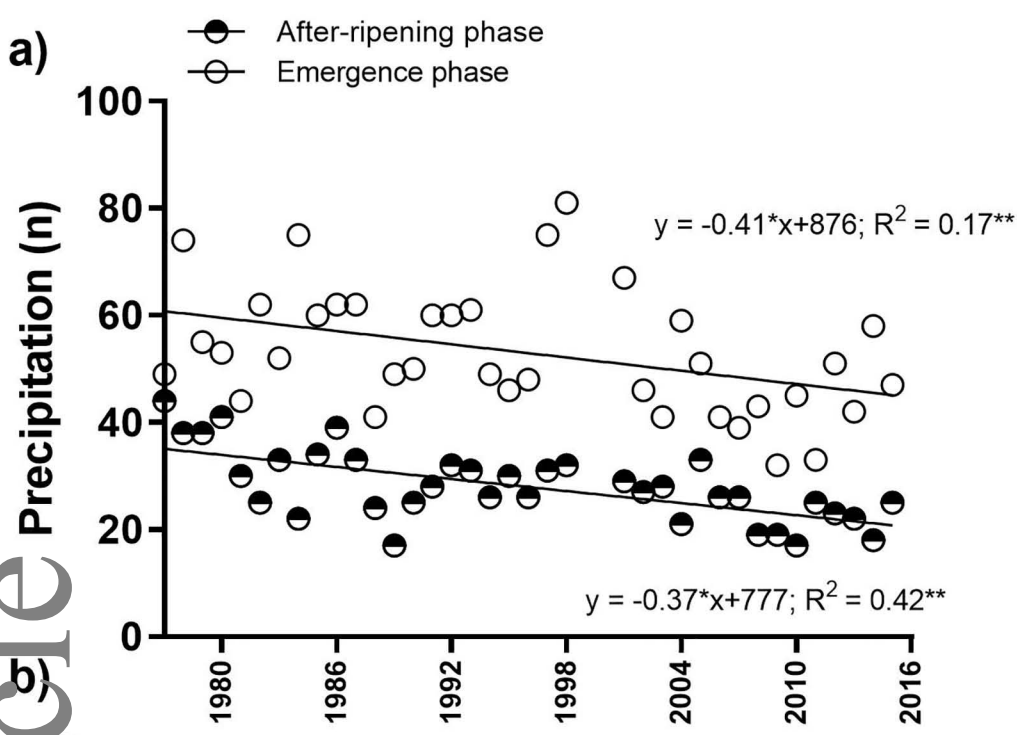


Table 1 Comparative values of *Avena fatua* seedling emergence traits for the staggered (Cluster 1), early (Cluster 2), medium (Cluster 3) and late (Cluster 4) patterns. Hydrothermal-time (HTT, MPa°Cd) and chronological time (days) to reach 10, 50 and 90% of cumulative emergence (CE) and the corresponding ‘emergence windows’ resulting from [90–10] are shown. Both chronological and hydrothermal-time accumulation start on 1 February (=zero emergence time).

| Emergence traits | Cluster | | | | <i>F</i> -test | <i>P</i> |
|---|---------------------|---------------------|---------------------|---------------------|----------------|----------|
| | 1-Staggered | 2-Early | 3-Medium | 4-Late | | |
| Hydrothermal-time to 10% CE | 600.8 ^c | 809.1 ^c | 1203.0 ^b | 1838.5 ^a | 37.38 | < 0.0001 |
| Hydrothermal-time to 50% CE | 1254.2 ^b | 1375.8 ^b | 2028.8 ^a | 2155.4 ^a | 18.52 | < 0.0001 |
| Hydrothermal-time to 90% CE | 1724.4 ^b | 2225.3 ^a | 2487.5 ^a | 2354.1 ^a | 8.34 | 0.0003 |
| Emergence windows (HTT ₉₀ -HTT ₁₀) | 1123.6 ^a | 1416.2 ^a | 1283.6 ^a | 515.6 ^b | 7.45 | 0.0006 |
| Days to 10% CE | 44.5 ^c | 49.0 ^c | 69.8 ^b | 115.0 ^a | 59.31 | < 0.0001 |
| Days to 50% CE | 124.8 ^b | 86.2 ^c | 142.7 ^{ab} | 167.8 ^a | 9.62 | 0.0001 |
| Days to 90% CE | 219.8 ^a | 167.7 ^b | 203.8 ^a | 201.6 ^a | 10.36 | 0.0001 |
| Emergence windows (days) | 174.3 ^a | 118.7 ^b | 136.1 ^b | 86.6 ^c | 20.88 | < 0.0001 |

Means marked with the same letters (a,b, and c) do not differ by LSD test ($P \leq 0.05$).

Table 2 Comparative values of climate data (1976–2015) for the staggered (Cluster 1), early (Cluster 2), medium (Cluster 3) and late (Cluster 4) patterns. Climate data were divided to account for phase AR (seed formation/maturing and after-ripening) and phase E (germination and seedling emergence).

| Climate variables | Cluster | | | | <i>F</i> -test | <i>P</i> |
|---|--------------------|---------------------|---------------------|--------------------|----------------|----------|
| | 1-Staggered | 2-Early | 3-Medium | 4-Late | | |
| Phase AR (October-to-January) | | | | | | |
| Mean minimum temperature (°C) | 11.4 | 12.2 | 11.9 | 12.0 | 2.10 | 0.1179 |
| Mean maximum temperature (°C) | 26.1 | 26.4 | 26.0 | 26.1 | 0.12 | 0.9490 |
| Mean average temperature (°C) | 18.8 | 19.3 | 19.0 | 19.0 | 0.45 | 0.7208 |
| Daily thermal amplitude (°C) | 14.7 | 14.2 | 14.1 | 14.0 | 0.45 | 0.7179 |
| Heat-stress units (°Cd) | 102.4 | 102.9 | 88.8 | 74.1 | 0.46 | 0.7147 |
| Precipitation (n° of events) | 23.7 ^b | 29.7 ^a | 29.0 ^a | 34.0 ^a | 4.14 | 0.0132 |
| Seed formation/maturing (mm) (Oct-to-Nov) | 11.4 ^b | 15.1 ^a | 14.9 ^a | 16.7 ^a | 3.13 | 0.0382 |
| Field after-ripening (mm) (Dec-to-Jan) | 12.3 | 14.6 | 14.1 | 17.4 | 1.73 | 0.1799 |
| Precipitation (mm) | 301.7 ^b | 387.1 ^{ab} | 303.7 ^b | 502.9 ^a | 4.38 | 0.0103 |
| Seed formation/maturing (mm) (Oct-to-Nov) | 136.8 ^b | 155.8 ^b | 142.4 ^b | 262.6 ^a | 2.89 | 0.0497 |
| Field after-ripening (mm) (Dec-to-Jan) | 165.1 | 231.4 | 161.4 | 240.8 | 1.31 | 0.2862 |
| Phase E (February-to-November) | | | | | | |
| Mean minimum temperature (°C) | 6.5 ^b | 7.3 ^a | 7.1 ^a | 7.2 ^a | 3.16 | 0.0370 |
| Mean maximum temperature (°C) | 19.8 | 19.7 | 18.8 | 20.0 | 1.71 | 0.1831 |
| Mean average temperature (°C) | 13.1 | 13.5 | 12.9 | 13.6 | 1.21 | 0.3203 |
| Daily thermal amplitude (°C) | 13.3 ^a | 12.4 ^{ab} | 11.8 ^b | 12.7 ^{ab} | 3.48 | 0.0262 |
| Heat-stress units (°Cd) | 59.3 | 50.9 | 39.3 | 35.5 | 1.74 | 0.1777 |
| Precipitation (n° of events) | 43.4 ^b | 56.8 ^a | 62.3 ^a | 57.4 ^a | 5.06 | 0.0053 |
| Autumn (n) | 15.6 | 18.0 | 19.8 | 17.2 | 1.94 | 0.1418 |
| Winter (n) | 12.8 ^b | 18.2 ^{ab} | 21.8 ^a | 17.6 ^{ab} | 2.97 | 0.0452 |
| Spring (n) | 15.1 ^b | 20.6 ^a | 20.7 ^a | 22.6 ^a | 4.84 | 0.0066 |
| Precipitation (mm) | 447.8 ^b | 608.4 ^a | 614.8 ^a | 612.8 ^a | 2.96 | 0.0462 |
| Autumn (mm) | 201.8 | 233.4 | 270.6 | 308.6 | 1.87 | 0.1530 |
| Winter (mm) | 65.8 ^c | 158.1 ^a | 137.2 ^{ab} | 80.0 ^{bc} | 6.34 | 0.0016 |
| Spring (mm) | 180.7 | 216.9 | 207.3 | 224.4 | 0.40 | 0.7557 |

Means marked with the same letters (a,b, and c) do not differ by LSD test ($P \leq 0.05$).