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RESEARCH ARTICLE

*Amaranthus* spp.: a genus of troublesome weeds

# Thermal time and extreme weather events determine the emergence of *Amaranthus palmeri*

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Abstract: **Background:** *Amaranthus palmeri* has emerged as the most widespread weed of agricultural land in large parts of North and South America. Understanding its population dynamics and the influence of meteorological variables becomes important for decision-making in an integrated management context. The hypothesis is that the emergence of *A. palmeri* is influenced by thermal time and extreme weather events that occurred in the previous 45, 30 or 15 days.

**Objective:** The work was aimed to detect the influence of meteorological variables and extreme weather events on the emergence of *A. palmeri* under field conditions.

**Methods:** A field experiment was carried out in order to record seedling emergence of *A. palmeri* in two growing seasons, 2017/2018 (S1) and 2018/2019 (S2), in Argentina. Associations between weed emergence and thermal time (in growing degree-days GDD), meteorological variables or extreme weather events recorded at 15, 30 and 45 days before to each evaluation time were studied by regression, principal components and multiple correspondence analyses.

**Results:** Thermal time was closely associated to the progress of cumulative emergence in both seasons, but the emergence periodicity was conditional with rainfall. The high precipitation during the spring determined a short lag period (121.8 GDD) in S2. Contrarily, the largest lag period (236.6 GDD) was detected in S1 related to a drought that concentrated the emergence in the beginning of the summer when the rainfall increased.

**Conclusions:** Thermal time allows the cumulative emergence prediction; however, extreme weather events like drought induce quiescence, concentrating the emergence in a short period.

**Keywords**: cumulative emergence; drought; Palmer amaranth; rainfall; soil temperature.

## 1. Introduction

In recent decades, *Amaranthus palmeri* S. Wats. has emerged as the most widespread weed of agricultural land in large parts of North and South America (Ward et al., 2013; Gaines et al., 2020). Although it is native to the Sonoran desert, its ability to tolerate adverse conditions and the evolution of resistance to several herbicides explain its expansion across wide regions (Ward et al., 2013). Since 2013, *A. palmeri* has been reported as an important weed in croplands of Brazil, Uruguay and Argentina (Morichetti et al., 2013; Carvalho et al., 2015; Gaines et al., 2020). Its resistance to glyphosate and other herbicides facilitated its survival and spread in soybean and cornfields (Larran et al., 2017; Palma-Bautista et al., 2019) and the environmental conditions of large areas of South America seem to be no constraint to its naturalisation.

Knowledge of the weed dispersal process and population dynamics becomes important for decision-making in an integrated management context, and models are used to understand, predict or evaluate weed population responses on a rational basis (Bagavathiannan et al., 2020). Associations among the emergence periodicity of weeds, agronomic practices and meteorological events have arisen, which are relevant for the use of pre-emergence herbicides for the control of multiple herbicide-resistant weeds (Beckie et al., 2019; Houston et al., 2021). Mechanistic models that explain the process of seed dormancy, germination and emergence as functions of environmental variables are the most difficult models to develop because they integrate variables of the edaphic environment, physiology of seed germination and interactive effects, while empirical approximations that associate microclimate variables and seedling emergence are highly valued (Forcella et al., 2000). However, detecting meteorological events that have the greatest predictive power on weed emergence is the first challenge (Grundy, 2003). In that sense, thermal time has been proposed to predict the emergence of *A. palmeri* in different environments (Piskackova et al., 2021).

Despite great efforts, the behaviour of invasive weed species in an uncertain climate is unclear (Ziska et al., 2011; Ramesh et al., 2017). In general terms, it is presumed that invasive plant species are better prepared than native weeds to adapt to the changing climate and its extreme weather events (Clements, Jones, 2021).

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Stone (2021) indicates that any event in the climate system that is episodic in nature and is far from average in some standard climatological measure is defined as an extreme weather event. Precisely, the Intergovernmental Panel on Climate Change defines the extreme weather events "as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations" (Field et al., 2012). The intensity, frequency and spatio-temporal extension of extreme weather events are related to climate change and represent a clear threat to agriculture (Cogato et al., 2019). In a particular region, the community of weeds composed by native and naturalised species can be shifted after suboptimal conditions determined by extreme weather events, opening niches to invasive weed species (Ramesh et al., 2017). On the other hand, these events can concentrate pulses of weed emergence due to unfavourable environmental conditions inhibiting the germination in some periods, and when the average conditions have re-established, the emergence is stimulated (Hartzler et al., 1999).

In relative terms and according to its region of origin, *A. palmeri* is well adapted to growth under regimes of low rainfalls, low inter-specific interference and low fertility levels (Leon, 2020). Consistently, projections under climate change scenarios highlight several agricultural regions of increasing and emerging risk from *A. palmeri* (Kistner, Hatfield, 2018). In croplands of northwestern Argentina, the high spread of *A. palmeri* was averted since the 2010/2011 crop cycle when the occurrence of dry periods favoured this species to the detriment of low production of soybean, corn, sorghum as well as native and naturalised weed species. The hypothesis is that the emergence of *A. palmeri* is influenced by thermal time and extreme weather events that occur in the previous 45, 30 or 15 days. In this context, the current work was aimed to detect the influence of meteorological variables and extreme weather events on the emergence of *A. palmeri* under field conditions.

## 2. Materials and Methods

### 2.1 Experimental field and design

A field experiment was carried out during two consecutive seasons, 2017/2018 (S1) and 2018/2019 (S2), in Las Breñas Experimental Station of INTA (27°05' S and 61°06' W), Chaco Province, Argentina. A naturalised *Amaranthus palmeri* population was discovered five years ago in the experimental field. The soil was classified as Haplustol oxico (Tizón series), and the previous crop to the establishment of the experiment was soybean in both years. The field was cultivated with a soybean-corn or sorghum sequence of five years under minimal or no tillage.

Ten sample areas were established at random where fixed frames (0.5 × 0.5 m) were installed in September of both years. Seedling emergence of *A. palmeri* was recorded weekly during seven months in S1 and S2. After each evaluation time, the seedlings were removed by hand. Data of weed emergence was in seedlings per square metre (n = 10).

### 2.2 Meteorological variables and determination of extreme weather events

Daily measurement of maximum and minimum air temperature, soil surface temperature (at 5 cm), accumulated rainfall, relative humidity (RH), dew point, effective and relative heliophany, wind speed, vapour pressure, evapotranspiration (ETP) and irradiance were recorded by the "Emilio Druzianich" meteorological station placed in the experimental station.

Fourteen extreme weather events were determined as the count of frost days (<8°C) and summer days (>25°C) and range of temperature (maximum temperature – minimum temperature), count of days with a vapour pressure higher than 15 and lower than 20 hPa, count of days without rainfall and count of days with accumulated rainfall higher than 1 mm and 10 mm (PP < 1 and PP = 10, respectively), number of days with RH lower than 40% and higher than 40% as well as the number of days with wind speed lower than 8 km h$^{-1}$ and higher than 13 km h$^{-1}$. All weather events were determined in three periods of 15, 30 and 45 days previous to each evaluation time of seedling emergence.

### 2.3 Modelling based on thermal time

According to the occurrence of *A. palmeri* seedling emergence, data were obtained on 20 times of evaluation in each season (S1 and S2). Following the methodology described by Piskackova et al. (2021), the cumulative emergence was associated with the thermal time starting July 1 (two months before to the first emergence recorded) and measured in growing degree-days (GDD) according to:

$$GDD = \sum_{i=1}^{n} (T_{mean} - T_{base})$$

where $T_{\text{mean}}$ represents the daily mean soil temperature (°C) at 5 cm depth and $T_{\text{base}}$ is 15°C (Piskackova et al. 2021). For the sum, when $T_{\text{mean}}$ was lower than $T_{\text{base}}$, GDD was zero. Cumulative emergence data were used to build a curve fixed to the Gompertz equation:

$$y = ae^{-e^{-\frac{x - x_0}{b}}}$$

where $y$ is the relative cumulative emergence, $a$ is the maximum relative cumulative emergence ($a$ = 1), $x$ is the thermal time (GDD), *x0* parameter represents the lag period and $b$ parameter is the rate of increase once emergence. The model was fixed for each season using GraphPad Prism® v 5.00 (GraphPad Software, Inc). The accuracy of the models was determined by analysing the F-test for model significance, residual variance analysis and coefficient of determination ($R^2$).

### 2.4 Effect of meteorological variables and extreme weather events on *A. palmeri* emergence

A quantitative analysis of associations between meteorological variables or extreme weather events and *A. palmeri* emergence was executed in two steps. Firstly, meteorological variables were analysed in S1 and S2, while subsequently the influence of weather events was considered for both seasons together and separately. A principal component analysis and multiple correspondence analyses were carried out in both steps. To execute the multiple correspondence analyses, data of emergence and meteorological variables were categorised in three groups: low, medium and high according to the 33%, 66% and 90% percentiles, respectively. Biplots were obtained because of principal component analyses and multiple correspondence analyses. Complementarily, a K-means clustering was carried out to determine which variables could make the most contribution to the *A. palmeri* emergence. All analyses were conducted in R (R Core Team, 2017).

## 3. Results and discussion

### 3.1 Environments and *A. palmeri* emergence

The meteorological variables recorded in both years of analysis were compared. The averages of air and soil temperatures for the period of September to March showed differences of one degree or lower between S1 and S2. Comparing monthly temperatures, the biggest difference was 3.4°C, detected in soil temperatures of November. Rainfalls recorded during S2 were higher than S1 (1595.2 mm versus 735.4 mm), and S1 only accumulated more water than S2 during February. Consistently, RH, vapour pressure and dew point were lower in S1 compared to S2, and the most heliophany and global radiation were recorded in S1. Although the mean wind velocity was greater in S2, the daily ETP of the period was slightly lower in this season (supplementary material).

The period of *A. palmeri* emergence started on the second week of October and the first week of September in S1 and S2, respectively. In both cases, this period showed an extent of around five months. The number of accumulated seedlings was similar in both seasons during the first two months since the beginning of the emergence period, where the daily emergence rate was 6.5 and 6.0 seedlings $m^{-2}$ in S1 and S2, respectively. Later the *A. palmeri* seedling occurrences were higher in S1, and the daily emergence rate increased to 18.8 seedlings $m^{-2}$ during January and February. Ten percent of the accumulated emergence was recorded in the last 20 and 70 days of the period in S1 and S2, respectively. As a result of this, a total of 1653 seedlings $m^{-2}$ were recorded in S1 and 630 seedlings $m^{-2}$ were accumulated in S2 (Figure 1a). From the total seedlings recorded in each season, 76% of the emergence occurred during the second half of the September-March period in S1, and 77% of seedlings detected in S2 had emerged during the first half of the period (Figure 1b).

### 3.2 Relative cumulative emergence as a function of thermal time

In general terms, germination occurs from non-dormant seeds that accumulated a specific thermal time at a determined soil water potential (Bradford, 2002). Current results show that cumulative *A. palmeri* emergence was closely associated with thermal time in both seasons, and the Gompertz model was fixed to the data obtained in each experiment. A delay in the initial emergence detected in S1 against S2 was detected comparing $X_0$ parameters, and the lag period was two times higher in S1. This difference can be explained by the rainfall accumulation during September and October (supplementary material) when the first emergence pulses were detected in S2 and S1, respectively (Figure 2). In that light, soil moisture has been pointed out

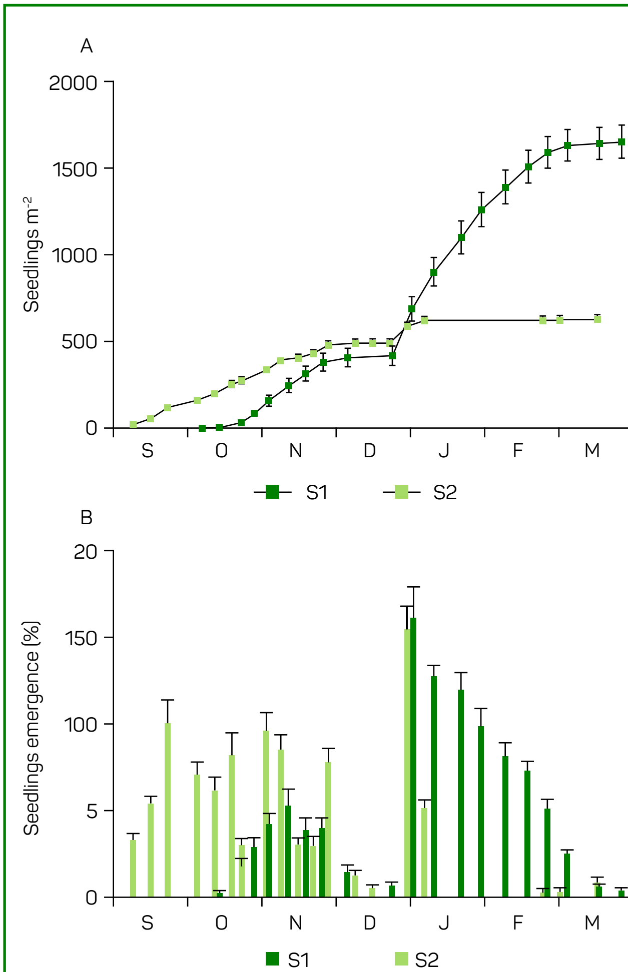


**Figure 1** - Seedling emergence of *Amaranthus palmeri* for each season (S1 and S2) on chronological time: cumulative seedlings (a) and emerging cohorts as a percentage of the cumulative emergence at the end of the season (b). Vertical bars indicate the standard error of the mean (n = 10)

as the single best predictor of *A. palmeri* emergence (Franca, 2015). Added to this, however, in the current results, the rate of increase emergence (*b* parameter) was around two-fold higher in S1 compared to S2 (Table 1). The emergence response would be more effective when the lag period was higher, and this process occurs under upper temperatures at the end of the spring to the begging of the summer.

Fifty percent of the cumulative emergence was recorded at 301 GDD; meanwhile, this level was reached at 155 GDD in S2. Recently, Piskackova et al. (2021) demonstrated that *A. palmeri* emergence can be predicted in different environments using thermal time, and 50% of the cumulative emergence occurred at 278 GDD in North Carolina State (USA). The results obtained in the current work agree with this antecedent, where *A. palmeri* emergence is associated with thermal time calculated from the daily mean soil temperature at 5 cm depth with 15°C as base temperature. However, the differences between model parameters fixed in S1 and S2 suggest that other environmental factors could modulate the emergence response (Table 1). To understand the combined effect of temperature and water potential on emergence, hydrothermal time models have been applied (Liu et al., 2019). These models demonstrate that germination does not take place below or above certain temperature and water potential thresholds. In that sense, this approach would be considered for explain the higher lag period recorded in S1 compared to S2. Using soil moisture sensors, the base moisture for *A. palmeri* emergence (0.11 $m^3$ $m^{-3}$) was defined by Piskackova et al. (2021) and thermal time models predicted the emergence over diverse environments when this water threshold was reached.

**Table 1** - Model parameters for cumulative emergence ($b$ and $x_0$) in both seasons of analysis (S1 and S2). Average values ± standard error are shown. The determination coefficient and P-value for model accuracy are indicated

| | S1 | S2 |
|---|---|---|
| $b$ | 176.0 ±16.0 | 92.7 ±4.9 |
| $x_0$ (GDD) | 236.6 ±14.7 | 121.8 ±7.0 |
| $R^2$ | 0.96 | 0.98 |
| P-value | <0.01 | <0.01 |

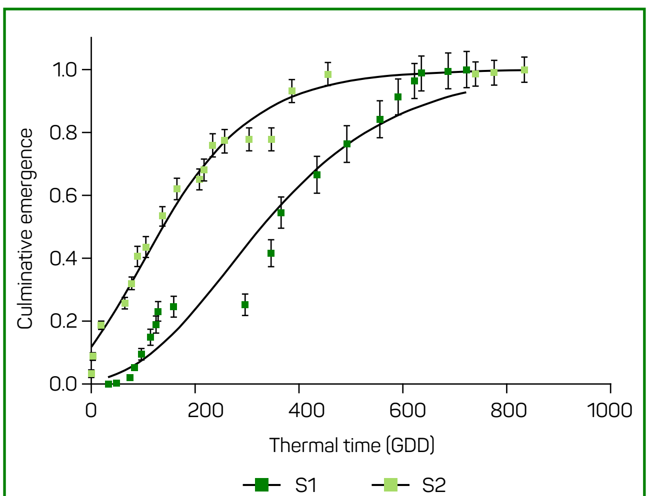


**Figure 2** - Cumulative emergence for each season (S1 and S2) based on thermal time. Symbols represent mean values (n = 10). The predicted responses are shown by lines according to the Gompertz equation (Table 1). The vertical bars represent the standard error of the mean

### 3.3 Relationship between meteorological variables and *A. palmeri* emergence

In a first approximation, the major *A. palmeri* emergence was found in the season of lower rainfall accumulation. However, as discussed above, a delay in the emergence period was highlighted in S1 compared with S2, and seedling emergence could be stimulated and concentrated by the higher summer temperatures (supplementary material). In that sense, *A. palmeri's* emergence response was positively correlated to maximum, medium and minimum temperatures in S1. Among those variables, the medium temperature was the variable highest associated with the *A. palmeri* emergence (Figure 3). Contrarily, these relationships were not observed in S2, and the weed emergence was negatively correlated to the maximum, medium and minimum temperatures (Figure 3). Oddly, recorded rainfalls were not correlated to the response variable in both seasons. In contrast, heliophany, ETP, relative humidity, dew point and wind speed were consistently associated with the *A. palmeri* emergence in both years of analysis (Figure 3).

### 3.4 Interaction among meteorological variables and the influence on *A. palmeri* emergence

The interaction among variables was analysed by determining three categories of relationships: high, medium or low contribution of each variable on the level of response of *A. palmeri* emergence. Thus, this approach explained 44.6% and 36.0% of the variance in S1 and S2, respectively. In the first case, the high response of emergence was associated with the high level of maximum, medium and minimum air temperatures as well as soil superficial temperature. Meanwhile, low and medium responses of *A. palmeri* emergence were associated with medium and low rainfalls, high relative heliophany and high relative humidity (Figure 4). These associations are consistent with the models that linked the *A. palmeri* emergence to the thermal time as the main independent variable if the soil moisture was adequate (Piskackova et al., 2021). The current results suggest that soil water would be the factor that induces the germination and temperature acts to modify the speed at which water induces this process.

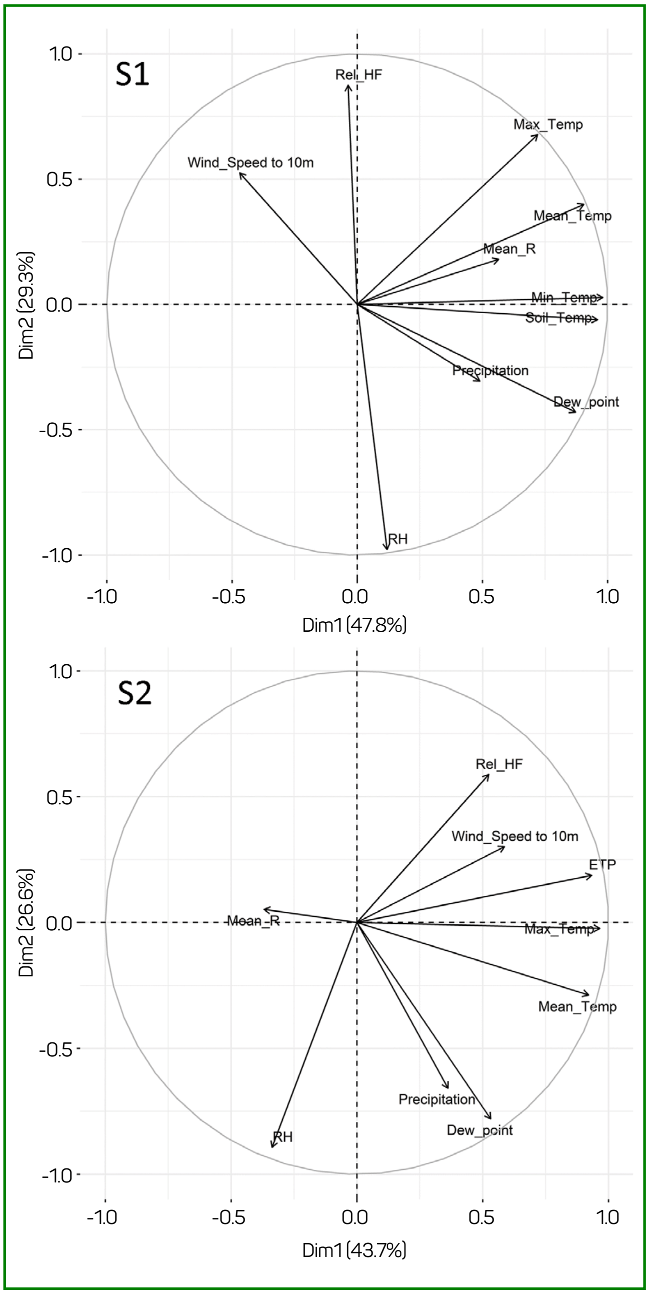


**Figure 3** - Principal component analyses for the effects of meteorological variables on *Amaranthus palmeri* emergence (Mean_R) in each season (S1 and S2)

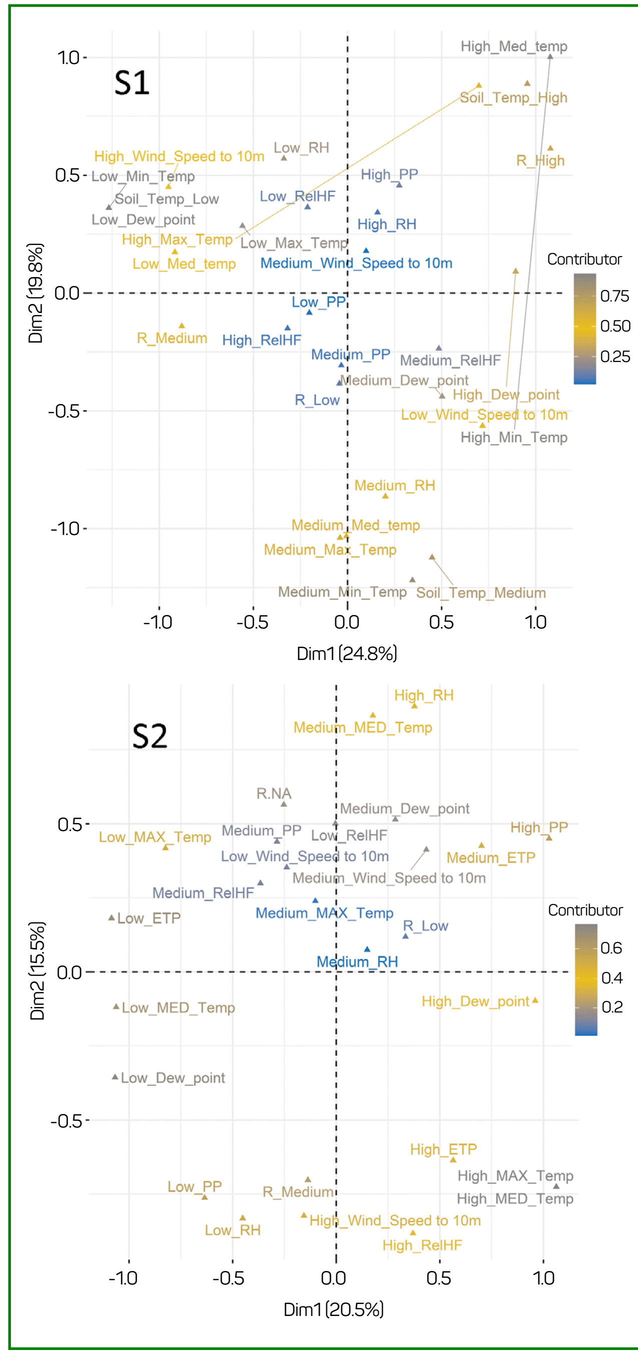


**Figure 4** - Multiple correspondence analysis plots showing the relationship among meteorological variables and *Amaranthus palmeri* emergence categorised as low, medium and high according to the 33%, 66% and 90% percentiles in each season (S1 and S2)

The influence of meteorological variables on the response of emergence in seedlings m$^{-2}$ was unclear in S2, and due to the highest precipitation occurring during September-November, the response could have been affected by the gradual accumulation of thermal time. In terms of density of *A. palmeri* emergence, S2 showed the lowest peak of the emergence of seedlings (maximum peak of emergence: 97 seedlings m$^{-2}$) compared to S1 (maximum peak of emergence: 270 seedlings m$^{-2}$). In that sense, Korres et al. (2018) have discussed the effect of soil moisture on the longevity of dormant seeds of *A. palmeri*, where this factor would be directly associated with the rate of seed mortality. In the current work, *A. palmeri* seedling density was highest in the season with the lowest accumulated rainfall. Thus, a concentration of emergence was seen in S1, where extreme meteorological events of drought could have maintained the seed viability and delayed the germination, triggering the highest flush of emergence in the summer.

### 3.5 Effects of extreme weather events on *A. palmeri* emergence

Extreme weather events recorded at 15, 30 and 45 days before each evaluation time were compared between seasons. The number of days with wind speed lower than 8 km $h^{-1}$ or higher than 13 km $h^{-1}$, the number of days with a vapour pressure higher than 15 and lower than 20 hPa and the number of days without rainfall showed no differences between S1 and S2. The number of days with rainfall and number of summer days (>25°C) were highest in S2 and S1, respectively. The range of temperature was different between seasons in certain periods. In the first four weeks of the emergence period, S2 showed the widest range compared to S1 and this relationship was inverted between the fourth to twelfth weeks of analysis. In both years, no cold days (<8°C) were recorded (Supplementary material).

Among the extreme weather events, what happened in the 15 days previous to each time of evaluation of weed emergence showed that the numbers of summer days and rainy days were directly related to the *A. palmeri* emergence in the S1 (Figure 5). This is consistent with hydrothermal time analysis where water potential and temperature are the two environmental regulators of seed germination (Alvarado, Bradford, 2002). The number of rainy days, including days with precipitation accumulated higher than 10 mm, was also associated with the response of *A. palmeri* in S2, but the number of summer days did not influence the dynamic of emergence considering the same period of 15 days previous (Figure 5). It is well known that water is a basic requirement for germination and seeds can germinate over a wide range of temperature if no water restrictions occur. In S1, the emergence showed the highest response in January and February (Figure 1b), when monthly accumulated precipitations were greater than 200 mm, and the summer day number reached its maximum. However, during S2, the rainy days triggered a peak of emergence early in the season (Figure 1b).

With increasing the period of analysis of extreme weather events to 30 or 45 days before a sampling time (Figure 6 and Figure 7), summer and rainy days were consistently associated with *A. palmeri* emergence in S1; however, the angle between the vector of response and these variables increased relative to the analysis of 15 days previous. Considering the relatively high speed of germination of *A. palmeri* under optimal conditions (Steckel et al., 2004), it is understandable that the influence of weather is determined by the environmental conditions near the emergence.

In S2, the number of days with wind speed higher than 13 km $h^{-1}$, number of frost days, low vapour pressure and low relative humidity as well as the range of temperatures recorded at 30 or 45 days previous were associated with *A. palmeri* emergence (Figure 7). In that sense, if the required moisture were ensured, the influence of fluctuating conditions would be conditioning factors of the emergence (Jha et al., 2010; Chahal et al., 2021). The effect of alternating temperature regimens on the stimulation of germination of this species has been demonstrated (Jha, Norsworthy, 2009). Interestingly, the

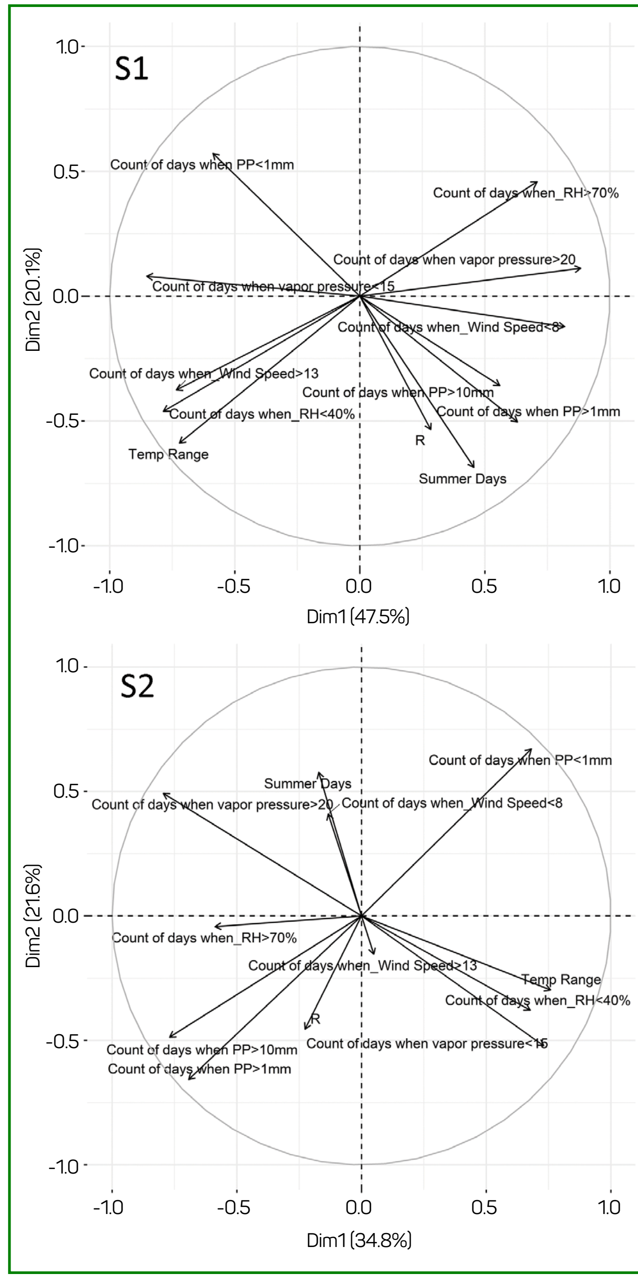


**Figure 5** - Principal component analyses for the effects of extreme weather events registered 15 days previous to each sampling time on *Amaranthus palmeri* emergence (R) in each season (S1 and S2)

association between temperature amplitude and emergence was observed in S2 when the availability of water was higher. The positive effect of the thermal amplitude on the emergence of *A. hybridus* has been associated with the adaptation of germination at the surface soil layer, where the seedling has more chance to emerge (Faccini, Vitta, 2007).

The principal components analysis explained between 55 and 77% of the variance depending on the period (15, 30 or 45 days previous) and season (S1 or S2) considered. The influence of extreme environmental factors would be hardly detected when analysing average meteorological variables, but it was in evidence in each season. The occurrence of rainfall seems to be the main factor that defined the differences between S1 and S2. According to the water availability in each season, the influence of extreme weather events, as the count of summer days or range of temperatures on *A. palmeri* emergence was highlighted.

Emergence studies of *A. palmeri* provide important information to support the optimal timing of weed control (Jha, Norsworthy, 2009; Piskackova et al., 2021). In *A. palmeri* populations from South America, the evolution of resistance to glyphosate and ALS-inhibitors herbicides implied the use of pre-emergent or bleaching herbicides to control seedling, where the current results can contribute to making an effective use of these weed control resources. Thus, predicting the main flush of emergence could maximize the efficacy of herbicides or cultural techniques as weed management practices.

## 4. Conclusions

The emergence periodicity and peaks that determine the progress of cumulative emergence of *A. palmeri* were conditioned by the rainfall occurrence. This meteorological


**Figure 6** - Principal component analyses for the effects of extreme weather events registered 30 days previous to each sampling timing on *Amaranthus palmeri* emergence (R) in each season (S1 and S2)

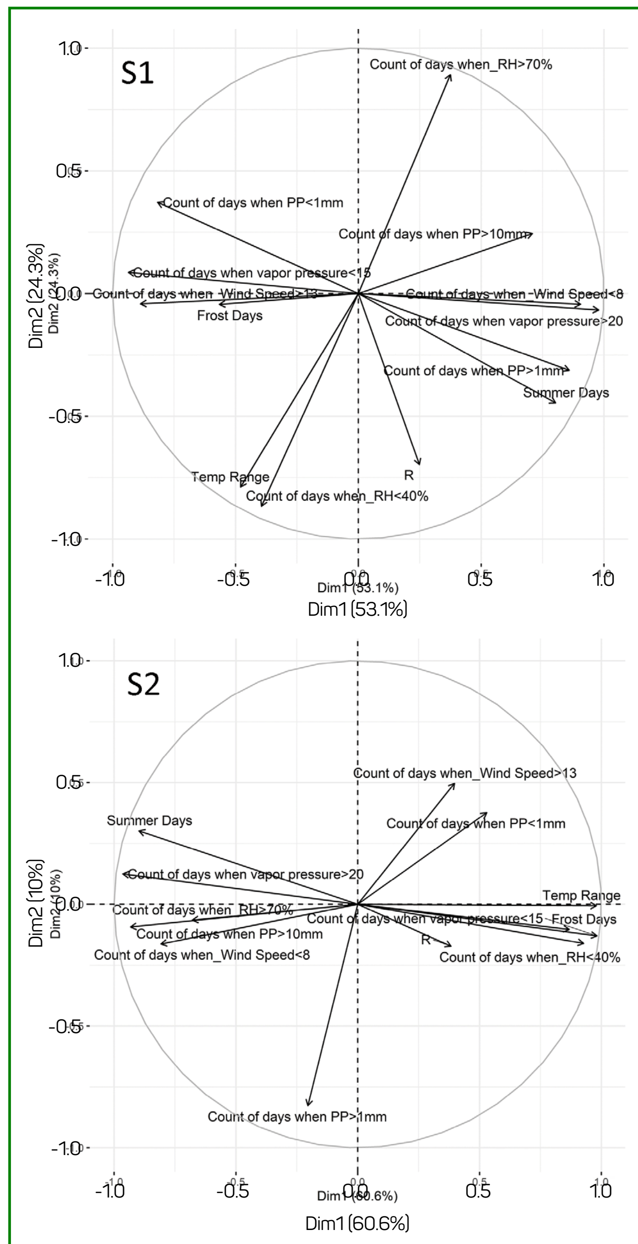


**Figure 7** - Principal component analyses for the effects of extreme weather events registered 45 days previous to each sampling timing on *Amaranthus palmeri* emergence (R) in each season (S1 and S2)

variable determined two types of environments in the seasons studied. The high monthly average rainfall during the spring stimulated premature emergence in S2. Thus, after a short lag period (121.8 GDD), the accumulation of thermal time was accompanied by the response in seedling emergence. However, the positive influence of alternating temperature regimens on the density of emergence recorded was also shown. A largest lag period detected in S1 was associated with the lowest precipitation. The drought delayed and concentrated the emergence in the beginning of the summer, an optimal environment for the *A. palmeri,* where the density of emergence recorded was tripled relative to S2.

In support of the hypothesis, the results demonstrate that the soil temperature at 5 cm is closely associated with the progress of cumulative emergence; however, extreme weather events, such as drought induce quiescence, delaying the emergence periodicity and concentrating the emergence in a short period. Currently, *A. palmeri* populations have evolved resistance to multiple herbicides, and several alternatives of control are based on pre-emergence herbicides. In this context, understanding *A. palmeri* seedling emergence is decisive to developing an efficient weed management strategy.

## Authors' contributions

All authors read and agreed to the published version of the manuscript. AL, MY, and MTS: conceptualization of the manuscript and development of the methodology. AL: data collection and curation. AL, MY, and MCF: data analysis. AL, MY, and MTS: data interpretation. AL, and MY: funding acquisition and resources, writing the original draft of the manuscript: MCF and MTS: writing, review and editing.

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