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# Arable Weed Patterns According to Temperature and Latitude Gradient in Central and Southern Spain

**María Luisa Gandía, Carlos Casanova, Francisco Javier Sánchez, José Luís Tenorio and María Inés Santín-Montanyá ***

Environment and Agronomy Department, National Institute for Agricultural and food Research and Technology (INIA), 28040 Madrid, Spain; gandia.mluisa@inia.es (M.L.G.); casanova@inia.es (C.C.); fsanchez@inia.es (F.J.S.); tenorio@inia.es (J.L.T.)
* Correspondence: isantin@inia.es

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**Abstract:** (1) Background: In agro-ecosystems, the success of the crops has a strong connection to biodiversity in the landscape. In the face of climate change, it is important to understand the response to environmental variation of weed species by means of their distribution. In the last century, biodiversity has been impacted due to a variety of stresses related to climate change. Although the composition of vegetation tends to change at a slower rate than climate change, we hypothesize species present in weed communities are distributed in diverse patterns as a response to the climate. Therefore, the general aim of this paper is to investigate the effect of temperature, using latitude as an indicator, on the composition and distribution of weed communities in agro-ecosystems. (2) Methods: Weeds were monitored in georeferenced cereal fields which spanned south and central Spanish regions. The graphic representation according to latitude allowed us to identify groups of weeds and associate them to a temperature range. We classified weeds as generalist, regional, or local according to the range of distribution. (3) Results: The monitoring of species led to the classification of weeds as generalist, regional or local species according to latitude and associated temperature ranges. Three weed species that were present in all latitude/temperature regions, were classified as generalist (*Linaria micrantha* (Cav) Hoffmanns & Link, *Sonchus oleraceous* L., and *Sysimbrium irium* L.). The species were classified as regional or local when their presence was limited to restricted latitude/temperature ranges. One weed, *Stellaria media* (L.) Vill., was considered a local species and its distribution dynamics can be considered an indicator of temperature. (4) Conclusions: The novel methodology used in this study to assign weed distribution as an indicator of climatic conditions could be applied to evaluate climate gradients around the world.

**Keywords:** agro-ecosystems; biodiversity; climate change; weed communities

## 1. Introduction

Biodiversity plays an important role in maintaining the processes and functions of ecosystems, including farming [1,2]. Plants respond to environmental conditions based on their needs in the habitat and physiological tolerances, which influences the composition of weed communities, their structure and resilience. In the last century, biodiversity has been impacted due to a variety of stresses related to climate change which have affected how and where species live, reproduce, and interact with each other [3,4]. The composition of vegetation tends to change at a slower rate than climate change, but nevertheless species present in weed communities have been distributed in diverse patterns according to their response to the climate [5].

Because climate change has influenced the annual productivity of many crops [6,7], as well as the composition and distribution of weed communities in agro-ecosystems [8,9], we can say that climate change presents both a threat to biodiversity and a cost in terms of weed control, for agriculture. Weeds are one of the main limiting factors of crop production worldwide, with part of their success being due to their plasticity: weed flora can adapt to changes in the environment [10–13]. This plasticity may respond to climate change at the local and regional level [14–16], and can act as a filter to soften the negative effects of a rapid change of climatic conditions in a particular area. In the short term, plasticity in the weeds allows them to cope with changes of environmental conditions.

Most of the agronomic actions in an agro-ecosystem has been designed to reduce the overall weed density [17–19]. However, the sustainability of cropping systems should be assessed not only in terms of crop yield but also adequate levels of biodiversity within cropland [20]. Agricultural practices, which vary according to local climate, cause a disturbance to the agro-ecosystem, and change the dynamics of the weed community, creating ecological niches [2,5,21,22]. These niches formed by weed communities affect plant diversity in the field [23,24]. Extreme weather combined with agronomic practices can lead to empty niches which present an opportunity for the establishment of new weed species [25,26]. The way that these niches are filled depends on the level of biodiversity. In agro-ecosystems with a greater diversity of weeds, there are more species available to fill these niches, which prevents any one species becoming dominant [27–29]. Logically, in agro-ecosystems with less diversity, it is easier for one weed species to take over a niche created by agricultural activity and become dominant. Weed diversity provides ecosystems services for the upper trophic levels in cropland ecosystems [23,30]. These changes in distribution of the weed community (abundance and richness) are often difficult to predict so monitoring changes is recognized as crucial both in stable and unstable environments. In the face of this challenge, several authors have argued that monitoring arable weed species can be used as biodiversity indicators in agro-ecosystems [31,32].

Studies on global warming have predicted a change in general temperature and rainfall patterns [33,34], but there are high levels of uncertainty about the nature of local changes. In Spain, temperature trend analysis confirms that there has been a widespread rise in annual average temperature since the mid-1970s, with warming being more apparent in winter (1.9 °C), and this increase in temperature in winter has given rise to longer growing seasons. One of the least explored aspects of global warming is its possible impact on the geographic distribution of agricultural weed species [35,36]. Climate change, and the consequent longer growing seasons, has led to the appearance of weed species which are more common in warmer conditions [24,37,38]. In this context, we have seen that the weed distribution patterns found in agro-ecosystems vary according to latitude, as influenced by temperatures gradients.

We hypothesize that climatic conditions are linked to weed species distribution. Although, studies have been conducted on the effects of climatic conditions on weeds, to our knowledge, relatively few studies have focused on weed distribution on regional and local scales. The objectives of this study were: (1) to implement a novel methodology; (2) to analyze the distribution pattern of weed species with respect to climate gradients and identify weed species as potential indicator of climate changes; and (3) to provide data regarding expected weed distribution changes due to global warmer for agricultural managers, in order to maximize yield parameters by maintaining biodiversity.

## 2. Material and Methods

In this study, we identified the weed species in cereal agro-ecosystems found in UTM quadrants of 10 km$^2$ (grid zones 29 and 30+, from latitude bands S and T). These quadrants were established within a North-South latitude range between Madrid (central Spain) 40.51 °N and Seville (southern Spain) 37.24 °N. We categorized plant species by latitude in a total of 50 quadrats.

This geographical range covers three latitudinal communities. The first two communities, located within Madrid and Castile La Mancha regions, are under Central Iberian plateau conditions. The altitude of the plateau is responsible for the existence of a continental Mediterranean climate. The most significant characteristics in these areas are severe winters, hot summers, summer drought, irregular rainfall, strong thermal oscillations and remarkable aridity. These features have been the result of the interrelations between geographical factors such as latitude, the situation of the region within the Iberian Peninsula, the relief layout and altitude. The annual thermal amplitude (difference between the average temperature of the coldest month and the hottest month) is very high, normally between 18 and 20 °C due to continentality. In July, the average monthly temperature is above 24 °C in most of the regions. The southern-most latitudinal community in the study, Andalusia region (Seville), has also semiarid conditions, similar to the continental Mediterranean climate but with more temperate conditions due to the coastal proximity.

The weed monitoring was carried out on georeferenced cereal fields, in the established route, during April 2018. The "time window" for the monitoring was decided according to the crop maturation stage. The cereal booting stage was selected because it is one of the critical competition stages in cereals [39], and the best time to identified weed flora representative of agro-ecosystems. All of the fields monitored, from central Spain were between 600 and 800 m in altitude and southern Spain fields were at an altitude range from 6 to 400 m. All the fields monitored showed the standard conventional management for each region.

To display the weed distribution along the latitude gradient a novel ordination methodology was performed on weed species present in the time of monitoring. A binary code was assigned to the presence or absence of weed species. The data was presented according to latitude (North–South) and the Tmax and Tmin were ordered from lowest to highest. Then, we represented these weed arrangements graphically (see the figures): where the peaks on the chart indicate the presence of weed species in a certain latitude or temperature. Also, the Spearman rank order correlation (Supplementary Materials) was used to obtain the relation between the weed species ordered by latitude and temperatures at the time window for monitoring, in the month of April.

In terms of temperatures, average maximum and minimum temperatures in April from the WorldClime database were reviewed, and data were adjusted to sea level. This method allowed us to classify and catalogue weed species according to environmental conditions, specifically different temperatures. This data analysis allowed for the identification of weeds that are able to tolerate high temperatures, these species, known as thermophilic, were found in latitude ranges that correspond to higher average temperatures. Other species were found not to thrive in the same conditions and weeds that are particularly sensitive to low temperatures and therefore have a reduced range of distribution were identified.

## 3. Results

A total of sixty-six weed species were observed in agro-ecosystems along our established route. The results of the process of categorizing weed species provided valuable information about distribution of weeds according to latitude and temperature. For the timing of weed monitoring, April 2018, the correlation between latitude and Tmax and Tmin were 0.749 and 0.790, respectively (in Supplementary Materials).

Figure 1 represents the findings of the sampling surveys. The peaks in the graph show presence of the weed species in the corresponding area. For this graphic representation we classified the weeds according to latitude. We can see three latitude ranges of 3 degrees (from 40.5° to 37.2°) which coincided with three regions of Spain called latitudinal communities: Madrid, Castile La Mancha, and Andalusia. We classified the weeds as local, regional and generalist, according to their range of dispersion:

(1) Local weed species were defined as restricted to a single latitudinal community (either Madrid, Castile La Mancha, or Andalusia), less than 33% of the geographical range.

(2) Species were classified as regional (two latitudinal communities) if they had a higher dispersion than local, between 33 and 66% of the geographical range.

(3) Generalists weeds were found in all areas of study, over three latitudinal communities, over 66% of the geographical range.

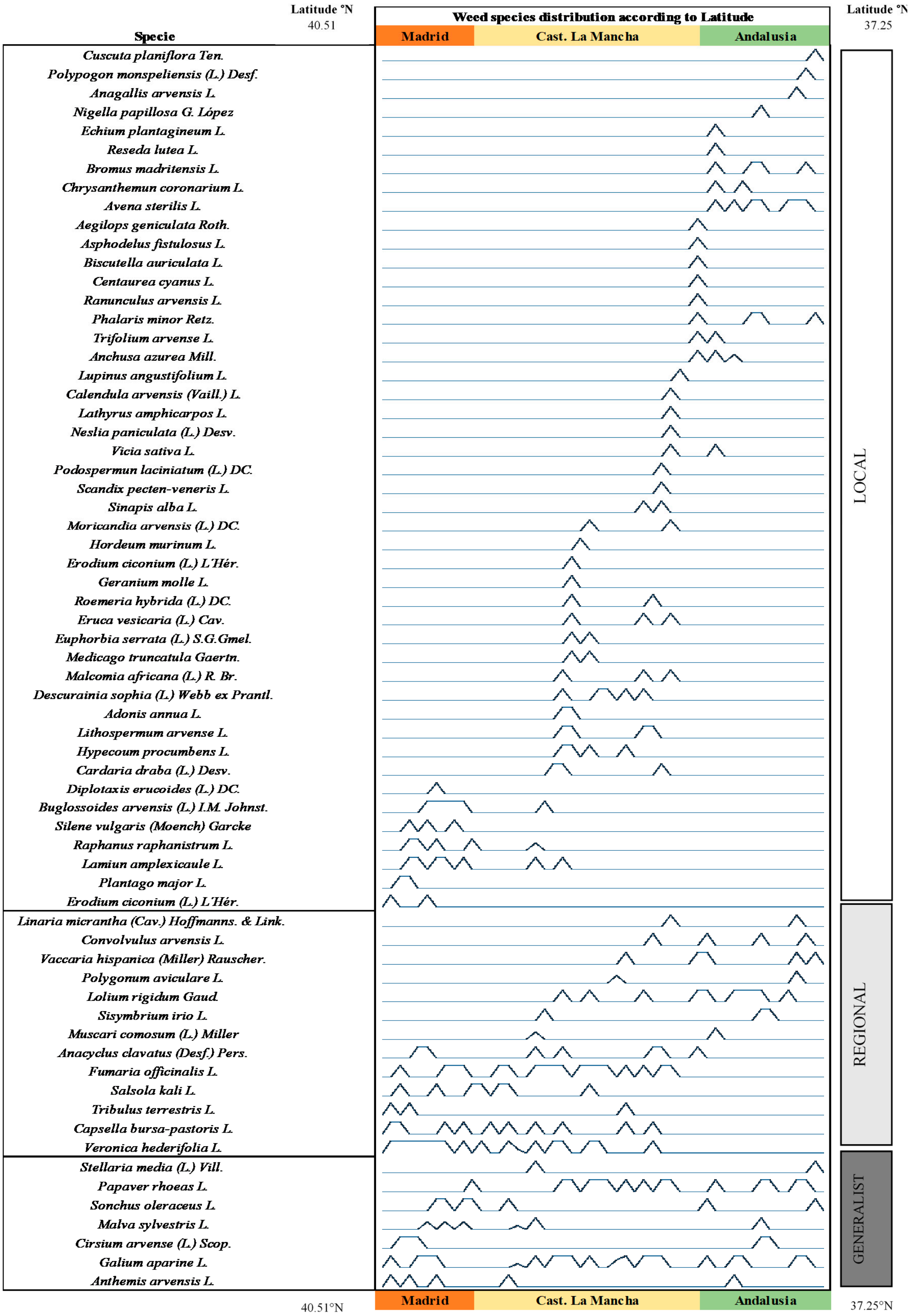


**Figure 1.** Graphical pattern of arable weed species distribution found in the studied areas according to latitude from Central to South of Spain (the peaks show presence of the weed species in the corresponding area).

Weed species were also divided into four groups by their thermal amplitude (species that appeared in up to 18, 36, 54 and 100% of Tmax and Tmin ranges), Figures 2 and 3 illustrate this. Figure 2 categorizes weed species according Tmax in April. The Tmax range was 4.7 °C (from 20.9 °C to 25.7 °C), and Figure 3 classifies weed species observed within a Tmin range of 4.1 °C (from 10.2 °C to 14.3 °C). The weed species were divided into four groups according to temperature: (1) weed species dispersed within a narrow temperature range, less than 18% of the total range; (2) weed species which were found within the 18–36% of temperature range; (3) weed species with more thermal amplitude, between 36 and 54%, and finally, (4) weed species present in all Tmax ranges. The classification of local, regional and generalist species had different results according to each of the three figures. We considered a species to be an indicator of temperature if its classification was the same in all three figures.

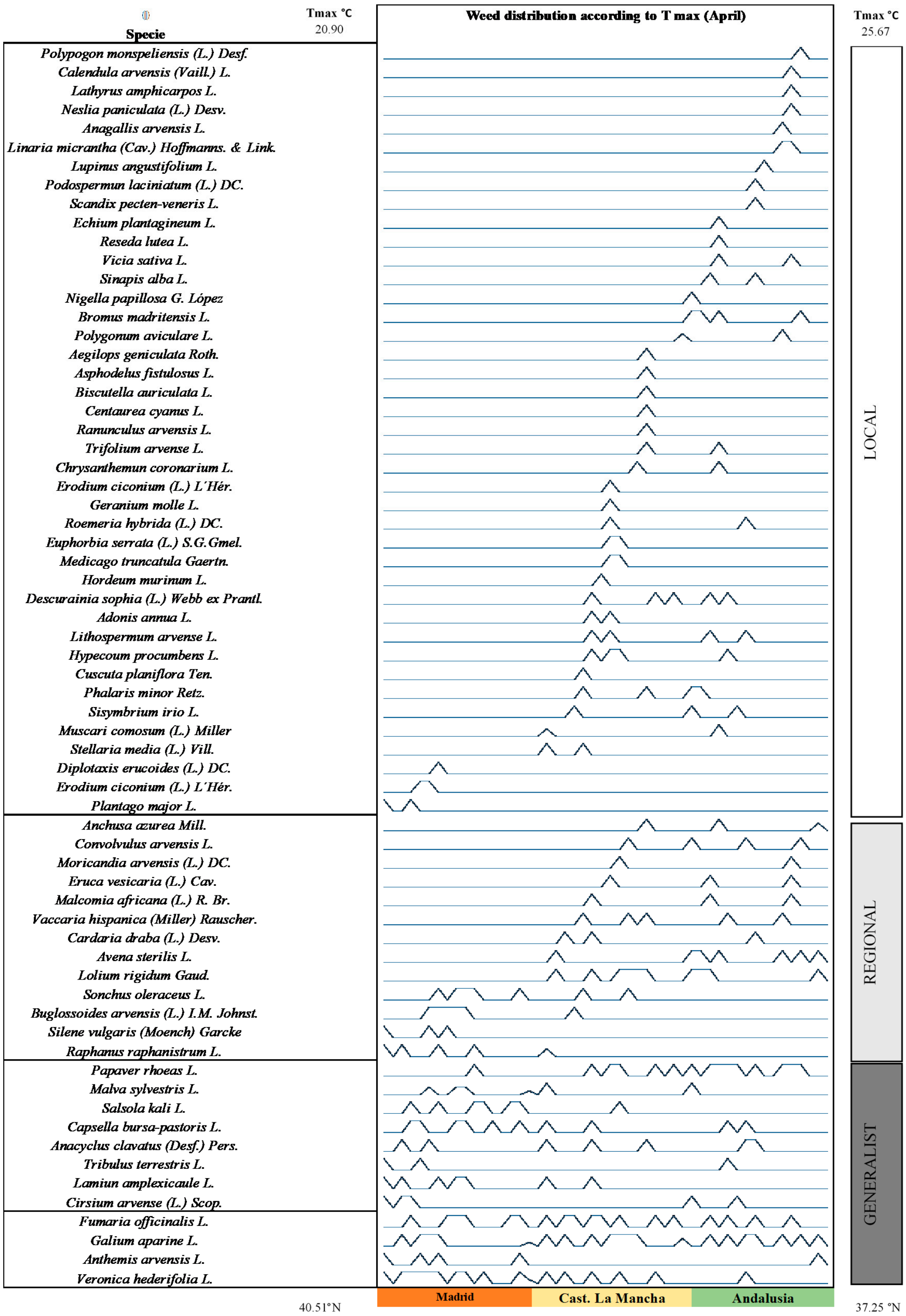


**Figure 2.** Graphical pattern of arable weeds distribution according to the Tmax in April.

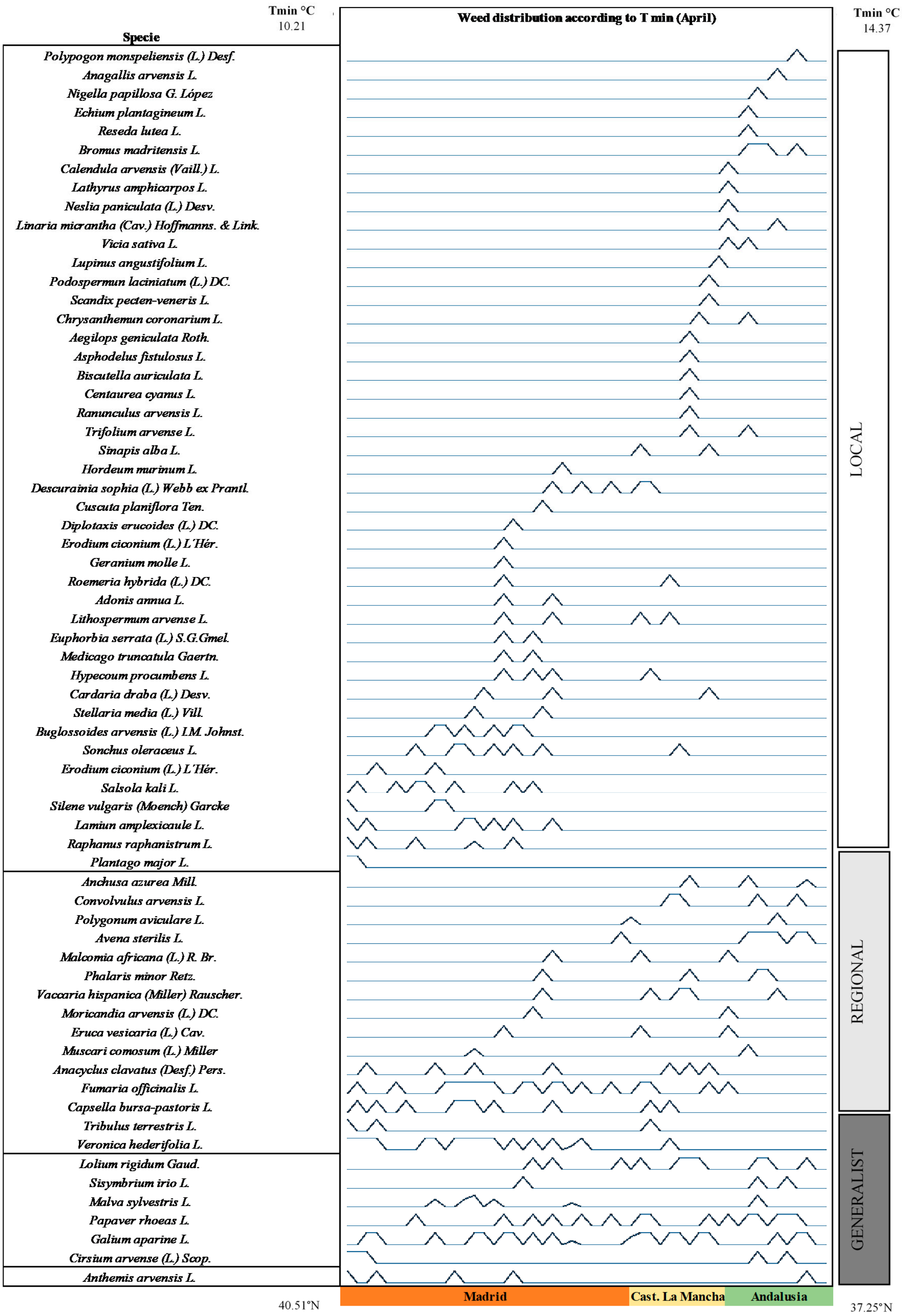


**Figure 3.** Graphical pattern of arable weeds distribution according to the Tmin in April.

According to latitude, *Anchusa azurea* Mill. and *Avena sterilis* L. were local species in Andalusia. *Moricandia arvensis* (L.) DC., *Eruca vesicaria* (L.) Cav. and *Malcomia africana* (L.) R.Br. were local species in Castile La Mancha. We consider these species to be potential indicators because their latitude ranges were narrow (≤33% of range) and also their dispersion of Tmax and Tmin range were between 18 and 36% (Figures 2 and 3, respectively). Other local species found were *Cardaria draba* (L.) Desv., *Blugossoides arvensis* (L.) I.M. Johnst., *Silene vulgaris* (Moench) Garcke, *Raphanus raphanistrum* L., and *Lamium amplexicaule* (L.). All of them were recorded in the latitude community of Madrid, 40° of latitude-north, with distribution within a geographical range corresponding to 33%, and 18% of dispersion in Tmin range. Local species were distributed in narrow ranges in terms of latitude and minimum temperature, however, a rise in average Tmin could favor their spread into more northern geographical ranges.

*Linaria micrantha* (Cav.) Hoffmanns. and Link. appeared as regional species, between 33 and 66% of dispersion within latitude range, and the variation in Tmax and Tmin ranges were narrower, ≤18%. In climate gradients where average temperatures are too high or too low, this weed species was not present. Then, global warming could completely change the geographical distribution of this weed species. *Sysimbrium irio* L. was observed as regional species, with similar variation in latitude and Tmin, but its Tmax range was very low (≤18%). When the maximum temperature is too high this weed species was not present. The opposite occurred with *Sonchus oleraceous* L., similar latitude and Tmax ranges variations, and Tmin range of ≤18%. When the average temperature was too low, this weed species was not present.

*Stellaria media* (L.) Vill. appeared in the highest latitude range (66–99%), but the narrowest Tmax and Tmin ranges (≤18%). We can state that this generalist weed is sensitive to temperature.

## 4. Discussion

Some weed species can share response patterns to particular environmental circumstances and hence affect their geographical distribution. Global warming, which implies longer growing seasons, may favor the appearance of weed species in regions which used to be colder [24,38]. Weeds sensitive to temperatures such as thermophilic weeds, or species with late emergence and opportunistic species can thrive now in some farming systems due to a rise in temperatures [5,8,9]. Numbers of these weed species have been increasing in northern areas because they are able to adapt to warmer conditions, and the growth cycle of these weeds has changed, accelerating the flowering stage [36–38,40–42].

On the other hand, climate change indirectly influences weeds that adapt to different agronomic practices. Frequently, we find that weeds are closely associated with the cropping system, and climate conditions have, therefore, an influence on the occurrence of weeds through crop management and land use [18,19]. From the above, we can deduce that the weeds that are present today in the agro-ecosystems are not necessarily the weeds that will be of concern in the future. However, further compilation of data regarding climatic conditions and the identification of weed flora in a determined area is necessary [26].

In this paper, we propose the implementation of a monitoring program for weeds in cereal systems, at a regional or local scale. It is important to facilitate the detection of changes within agro-ecosystems and allow farm managers the chance to predict the effects of climate change and reduce the impact on crop parameters. However, there is little information of the distribution of weed species [24,43], within the cereal agro-ecosystems, according to variables as latitude and temperature changes. Our study about weed distribution offers a resource to observe and compare weed species distribution in semiarid agro-ecosystems at the local level.

We found *Anchusa azurea* Mill., *Avena sterilis* L., *Moricandia arvensis* (L.) DC., *Eruca vesicaria* (L.) Cav., and *Malcomia africana* (L.) R.Br. as local species. We could consider these species as marker of warm conditions. If average minimum and maximum temperature increase, can be facilitated a thermophilic movement of these species and we would find these weeds relocated in other latitudes. *Avena* spp. has been categorized as aggressive grass in northern countries [12]. *Avena sterilis* L. is a widely spread weed by the Iberian Peninsula and has been principally controlled by herbicides. Its presence in the monitoring reflects its ability to adapt to warmer conditions. Therefore, the dispersal mechanisms of these species will have a great influence on their distribution and the plant traits of these local species should be object of future consideration.

*Cardaria draba* (L.) Desv., *Blugossoides arvensis* (L.) I.M. Johnst., *Silene vulgaris* (Moench) Garcke, *Raphanus raphanistrum* L., and *Lamium amplexicaule* L., were local species disperse in Tmin range narrowest. So, we think that Tmin can sorted the weed species within the observed latitude. Some authors [44,45] have found as local species *Silene noctiflora* due to propagule transport mainly relies on biological dispersal mechanisms and the habitat fragmentation prevent the dispersal of species.

*Linaria micrantha* (Cav.) Hoffmanns. and Link., *Sysimbrium irio* L. and *Sonchus oleraceous* L. were species more spread than others mentioned in this study. However, too low or too high temperatures may challenge their survival within their latitude, and so we could consider these three weeds (*Linaria micrantha*, *Sysimbrium irio,* and *Sonchus oleraceous*) as opportunistic because their presence is a function of optimal temperatures. Several *Sysimbrium* spp. species has been found in oilseed rape fields in Germany [38]. *Stellaria media* (L.) Vill. would also be considered a generalist species, widespread in all latitudes, but sensitive to changes in temperatures. *Stellaria media* (L.) Vill., as a nitrophilous species with shading tolerance has become relevant species in northern areas [12,46].

Temperature change reveals both the threat to biodiversity and the cost of weeds for agriculture. Because temperature has influenced the annual productivity of many crops, as well as the composition and distribution of weed communities in agro-ecosystems. These results demonstrate some degree of plasticity in response to environmental variation of weed species by means of their spatial distribution. Of course, the plants are integrated in agro-ecosystems, and these responses are influenced by other factors such as agronomic practices.

In view of the results, climate change poses an uncertainty about the best way to design weed management strategies. A static style of management cannot be assumed any longer, and an adequate management of weeds, in the future, must take into account temperature change, land use, and human activity. Changes in the composition of the weed community can reduce the effectiveness of existing control strategies, as well as yield and economic cost to producers due to uncontrolled weeds. Also, important ecosystem services provided by weeds can be compromised if the composition of the community evolves with climate change. The different weed distribution patterns found could, in the long term, lead to variations of ecosystem functions. Therefore, the estimation of the damage of the weeds in the agro-ecosystems will be very important to reduce its impact and develop management strategies, current and future, effective against climate change.

## 5. Conclusions

Our research supports the common view that the monitoring of biodiversity is a means to obtain information on the state and dynamics of the agro-ecosystem. The application of the novel methodology proposed has made it possible to visualize clear links between latitude and temperature ranges related to weed distribution. The monitoring method presented here can be a promising tool to supply information in bioclimatic distribution models of species that needs to be validated with empirical data on weeds under changing climatic conditions. Also, this methodology proposed may be applied to the study of climate gradients around the world.

We think that there are temperature sensitive weeds which can be used in further studies as indicators of climate change by comparing distribution to local and regional data. Considering that weed community changes are not always noticeable in the short term, we recommend establishing long-term monitoring to detect changes in the biodiversity of agro-ecosystems. Furthermore, any changes in weed distribution in the agro-ecosystem due to temperature changes would affect the crops. Therefore, any information about shifts of weed dynamics related to temperature changes is going to be especially important in the future for crop management.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2073-4433/11/8/853/s1, Figure S1: Distribution of weed species according Latitude (from South to North in *X*-axis) and temperatures. Spearman rank order correlation values with temperatures in April month = 0.749 (Tmax) and 0.7906 (Tmin).

**Author Contributions:** All authors contributed to the monitoring of species. M.I.S.-M. and M.L.G. performed the original draft preparation of the manuscript; M.I.S.-M. and C.C. conceived and designed the experiments and revised the whole manuscript; M.L.G., J.L.T., and F.J.S. contributed to the analysis de data and the design of the experiments. All authors have read and agreed to the published version of the manuscript.

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