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RESEARCH ARTICLE

Potential distribution of *Amaranthus palmeri* under current and future climatic conditions in Brasil and the world

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Abstract: Background: *Amaranthus palmeri* is an economically important plant species worldwide. The rapid growth and competitive potential of crops make *A. palmeri* a major problem. Studies on the dissemination potential of this weed in Brazil and worldwide are necessary to identify the regions with high climatic potential. Similarly, we analyzed the behavior of the species in the face of predicted climate change. Studies of this type can be performed using ecological niche modeling. **Objective:** This work aimed to determine areas with climatic suitability for *A. palmeri* in the present and future climates in Brazil and globally. **Methods:** We projected the potential distribution of *A. palmeri* based on the environmental requirements and stress parameters that limit this species in Brazil. **Results:** For the current climate, our model identified regions with favorable climatic suitability for *A. palmeri* on most continents. The results showed that the suitability of *A. palmeri* in the Brazilian territory will decrease owing to predicted climate change. The future model highlighted decreases in the suitable northern, northeastern, and midwestern areas. An annual study of the occurrence of *A. palmeri* using the weekly growth index predicted by the model showed great potential for the species throughout the year, with a decrease in the driest months (July to August), indicating the preference of the species for moist soils. Tropical and subtropical zones are currently experiencing a reduction in suitable areas because of climate change in northeastern Brazil and western Australia. Temperate zone sites have potential areas of expansion for *A. palmeri* (northern USA, Russia, and China) under climate change. **Conclusions:** Based on the results of this study, management strategies should be planned to contain the global spread of *A. palmeri*.

Keywords: CLIMEX; Pest; Risk analysis; Weeds

1. Introduction

Amaranthus palmeri is a weed native to the Sonora Desert in northern Mexico and southwestern United States (Sauer, 1957). Distribution also occurs in some countries in South America (Heap, 2021). Although the center of origin of this species is an arid region, *A. palmeri* is widely distributed and adapted to different climatic conditions (Iamonico, Mokni, 2017) and is considered one of the most feared weeds in the world (Singh et al., 2018). The rapid growth, high seed production capacity, and competitive nature of this species make *A. palmeri* very problematic in terms of control (Chahal et al., 2015). In addition, it is a host plant for parasitic nematodes (Kaspary et al., 2021). Therefore, owing to its direct and indirect damage to crops, *A. palmeri* is a weed of worldwide economic importance.

A. palmeri infestation can cause yield losses of more than 68% in soybean, 65% in cotton, and 91% in corn (Klingaman, Oliver, 1994; Berger, 2015; Massinga et al., 2003). *A. palmeri* has many herbicide-resistant biotypes, including simple, crossed, and multiple biotypes that are to the main herbicides used in agriculture (Burgos et al., 2001; Gossett et al., 1992; Culpepper et al., 2006; Netto et al., 2016). In the United States, a biotype resistant to seven mechanisms of action was identified (Montgomery et al., 2019).

Because of these characteristics, *A. palmeri* is considered a quarantined pest in several countries including in Brazil (MAPA, 2019). The first occurrence of *A. palmeri* in Brazil was in Mato Grosso in 2015 (Andrade Júnior et al., 2015). A likely hypothesis for the presence of this species in Brazil is the import of cotton pickers contaminated with *A. palmeri* seeds (Schwartz-lazaro et al., 2017; Gazziero, Silva, 2017). According to the Normative Instruction INDEA/MT No. 3 dated December 10, 2020, this weed is an officially controlled pest in Brazil. However, the risk of spread remains high.

Therefore, studies on the spread potential of *A. palmeri* in Brazil and worldwide are necessary to identify regions with climatic potential and the behavior of species in the face of predicted climate change. Such studies can be performed using ecological niche modeling. Using biological parameters, the space–time dynamics of *A. palmeri* can be projected in a simplified and realistic manner (Lima et al., 2009). Ecological modeling software such as CLIMEX has been used to project the potential distribution of species of economic interest and to determine the limiting factors for spatial distribution based on climatic variables. Using CLIMEX, it is possible to analyze the potential occurrence of

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weeds, climate change, and seasonal assessments, and identify suitable areas according to the season (Kriticos et al., 2015). Studies of this nature support technological innovations for understanding the relationship between invasive alien species and climate variability (Cavalcante et al., 2020).

The CLIMEX model for *A. palmeri* is available in the literature (Kistner, Hatield, 2018). However, to date, information regarding the occurrence of this weed, particularly in Brazil, has been lacking. Consequently, non-assertive control decisions may occur because the model predicts inaccurate areas for spatial distribution or areas with low suitability. We have also updated the geographic distribution of *A. palmeri* and potential areas for 2050, 2070, and 2100 while evaluating the weekly growth rate. This study aimed to design a new model of the potential areas for *A. palmeri* in Brazil and worldwide under current and future climatic conditions (2050, 2070, and 2100).

2. Material and methods

2.1 Distribution of Amaranthus palmeri

Distribution data for *A. palmeri* were compiled from the Global Biodiversity Information Facility (GBIF) (http://www.gbif.org) and the available literature. The data were used to build a spatial distribution map of *A. palmeri* and validate the model. A total of 422 occurrences were identified across North America, South America, Europe, Africa, and Asia (Figure 1).

2.2 Climex Modeling

CLIMEX is a semi-mechanistic modeling package that predicts areas of climate suitability for species (e.g., insects and plants) based on ecophysiological and distributional data (Kriticos et al., 2015). The Ecoclimatic Index (EI) indicates the general climatic suitability of a location for the occurrence of the species. Ecoclimatic Index EI = 0 indicates an unsuitable location site for the species to survive, 0 < EI < 30 indicates a partially suitable location for the occurrence of the species and 30 ≤ EI ≤ 100 indicates a location with high suitability, the potential for survival and reproduction. To project the potential distribution, mechanistic and semi-mechanistic models use biological information of the species, together with climatic variables and environmental stress tolerance, to define areas of climatic suitability and highlight the limiting factors for the potential distribution of the species (Kumar et al., 2014; Kearney and Porter, 2009). Knowledge of the location of a species can be used to predict tolerable climatic conditions (Silva et al., 2020). The CLIMEX software was used to elaborate on the *A. palmeri* model, which considers climatic conditions as the main limiting factor for species occurrence.

2.3 Tuning parameters

Our objective was to adjust the growth and stress indices in CLIMEX by updating the modeling values published by Kistner and Hatield (2018) using biological information and the current distribution of *A. palmeri* in Brazil (Table 1).

2.3.1 *Temperature Index*

The lower limit temperature for species survival (DV0) was adjusted to the new value of 5 °C because germination of *A. palmeri* occurs above this temperature (Ward et al., 2013). The lowest optimal temperature (DV1) was adjusted according to the results of (Guo, Al-Khatib, 2003), where strong growth of *A. palmeri* was demonstrated in the range of 30 °C. The upper ideal maximum temperature (DV2) was set at 34 °C. The maximum threshold temperature (DV3) was set at 42 °C to be consistent with the occurrence of *A. palmeri* in the Sonoran Desert.

Figure 1 - Global distribution of *Amaranthus palmeri* Global Biodiversity Information Facility (http://www.gbif.org) and the available literature

Table 1 - CLIMEX index values used for modeling *Amaranthus palmeri*

Index	Parameter	Low values	Best-fit values	High values	Unit
Moisture	SM0 = lower soil moisture threshold	0.09	0.1	0.11	-
	SM1 = lower optimum soil moisture	0.18	0.2	0.22	-
	SM2 = upper optimum soil moisture	1.08	1.2	1.32	-
	SM3 = upper soil moisture threshold	1.8	2	2.2	-
Temperature	DV0 = lower threshold	4	5	6	°C
	DV1 = lower optimum temperature	29	30	31	°C
	DV2 = upper optimum temperature	33	34	35	°C
	DV3 = upper threshold	41	42	43	°C
Cold stress	TTCS = temperature threshold	-7.2	-8	- 8.8	°C
	THCS = stress accumulation rate	- 0.00022	- 0.00025	- 0.00027	$week^{-1}$
Heat Stress	TTHS = heat stress temperature threshold	37.8	42	46.2	°C
	THHS = heat stress temperature rate	0.045	0.05	0.055	$week^{-1}$
Dry stress	SMDS = soil moisture threshold	0.09	0. 1	0.11	-
	HDS = stress accumulation rate	- 0.0009	- 0.001	- 0.0011	$week^{-1}$
Wet Stress	SMWS = soil moisture threshold	1.8	2	2.2	-
	HWS = stress accumulation rate	0.0018	0.002	0.0022	$week^{-1}$
Degree days	PDD = Degree days per generation	1080	1100	1120	°C

2.3.2 *Moisture Index*

A value of 0.1 is associated with permanent wilting of plants. However, as *A. palmeri* has a deep root system, the lowest moisture threshold (SM0) was set at 0.1 (Forseth et al., 1984). The lowest optimum moisture content (SM1) was set at 0.2 to reflect the regions with the highest occurrence of the species. The upper optimum moisture content (SM2) and upper threshold (SM3) were set to 1.2 and 2, respectively, to reflect field observations in Mato Grosso, Brazil.

2.3.3 *Cold Stress Index*

The temperature threshold for cold stress (TTCS) was set at -8 °C and the stress accumulation rate (THCS) at -0.00025 week-1 to demonstrate the dormancy of *A. palmeri* seeds when exposed to low temperature (Rana et al., 2017).

2.3.4 *Heat Stress Index*

The heat stress threshold (TTHS) was set at 42 °C and the heat stress accumulation rate (THHS) was set at 0.05 week-1 to allow the best fit of the model in sites of high *A. palmeri* occurrence.

2.3.5 *Dry Stress Index*

Considering the low relative humidity areas where *A. palmeri* occurs worldwide, the drought stress threshold (SMDS) was set at 0.1, and the drought stress accumulation rate (HDS) was set at -0.001 week-1 to allow the survival of this species throughout the Sonoran Desert and Africa.

2.3.6 *Wet Stress*

Increased soil water content is meaning factor for the growth and fertility of several weed species including *A. palmeri*. In this sense, the wet stress parameter (SMWS) was set to two to quantify the stress. The stress accumulation rate (HWS) was set at 0.002 weeks -1. These values were in agreement with the known distribution of *A. palmeri*.

2.3.7 *Degree Days*

Amaranthus palmeri requires 1,100 °C days to develop (Chahal et al. 2018). For this reason, we set the degree days per generation (PDD) at 1,100 °C days.

2.4 Climate data

The weather data used to manage the program were obtained from the CliMond 10. The A1B scenario and the CSIRO-Mk3.0 (CS) global climate model (CS) from the Center for Climate Research, Australia, were used to model the predicted climate change scenarios for 2050, 2070, and 2100. This model's choice is justified because it lies between scenarios A1 and A2. The A1B model considers rapid population and global economic growth and balances all energy sources (Kriticos et al. 2012). According to Meehl et al. (2007), A1B is the most pessimistic scenario for the period up to the middle of the 21st century (2050), compared to scenarios A1 and A2. The A1B scenario assumes greater greenhouse gas emissions, and consequently, a greater climate impact. It is estimated that the average temperature increases by about 1.8°C and carbon emissions are concentrated at about 580 ppm. By the end of the century (2100), the A1B scenario projected an average temperature increase of approximately 2.8 °C and CO2 emissions of 720 ppm. Vera et al. (2006) reported increased precipitation in South America (subtropical regions) during the summer and decreased rainfall during the winter.

The weekly growth index (GIW) of *A. palmeri* was also analyzed in the Brazilian regions where the species occurs. Monthly climate variation data were obtained from the Climate Research Unit (CRU) (CRU TS3.23, Norwich (http://www.cru.uea.ac.uk/cru/data/hrg.htm] Time-Series (TS), version 3.23). This dataset contains all the information necessary for use in CLIMEX software. The model was created from January 1 to December 31, 2016, the year following the discovery of the species in Brazil. To determine the growth potential of the species throughout the year and identify possible limiting factors, the weekly growth rate was estimated for the municipalities of Campos de Júlio, Sapezal, Tapurah, and Ipiranga do Norte in Mato Grosso, Brazil, from the meteorological station in the municipality of Comodoro-MT, which was chosen because it is closer to the cities studied and contains all data records.

2.5 Model validation

The reliability of this model was tested using the highest occurrence of *A. palmeri* in North America and the Ecoclimatic Index (EI) projected for the current climate. In addition, the areas of occurrence of *A. palmeri* in Brazil were considered for model validation.

2.6 Sensitivity analysis

For the sensitivity analysis, the parameters used in this model were adjusted to the high and low values proposed by the CLIMEX user guide. We used temperature values +/- 1 °C, soil moisture +/- 10% and rate parameters +/- 10%. The determination of these values is based on the best fit proposed by the software, the uncertainty of the parameters, and the parameter range of experienced CLIMEX users (Kriticos et al., 2015). The objective of the sensitivity analysis was to identify the parameters with the greatest influence on the results of the model. The EI was used to indicate potential area changes (unsuitable, suitable, and highly suitable) for *A. palmeri*.

3. Results

The potential distribution of *A. palmeri* in the current climate followed a known record of occurrence (Figure 1). Our model showed 100% agreement with the current distribution of *A. palmeri* in the validation area in North America (Figure 2). The current distribution of *A. palmeri* is primarily in tropical and subtropical zones. For the United States of America, Mexico, Argentina, Germany, and Brazil, the model correctly projected suitable areas at all sites of *A. palmeri* infestation (Figure 2 A). Large areas that were climatically suitable were observed in South, Central, and North America (except for Canada). On the African continent, especially in sub-Saharan Africa, some countries such as South Africa, Ethiopia, Kenya, Gabon, Mozambique, Cameroon, Central African Republic, Democratic Republic of Congo, Nigeria, Ghana, Uganda, Burkina Faso, Zimbabwe, Botswana, Namibia, and Madagascar have highly favorable areas for *A. palmeri* establishment (Figure 2).

In Europe, the regions with high climatic suitability for *A. palmeri* were Portugal, Spain, Russia, Poland, France, Italy, Austria, and Germany (Figure 2 A). On the Asian continent, the model projected areas in India, Myanmar, Thailand, and Indonesia where weeds have not yet occurred. China has a large area suitable for *A. palmeri*. In Oceania, suitable areas exist for *A. palmeri* on most of the continent, and projections have highlighted suitable areas in Australia and New Zealand (Figure 2A).

To predict climate change, we projected the potential global distribution of *A. palmeri* for 2050, 2070, and 2100. The projections showed a variation in the potential distribution of *A. palmeri* compared to the areas where the species is present. We observed that all Brazilian regions are suitable for the occurrence of *A. palmeri*, based on the EI. In Figure 3 B (2050), 3 C (2070), and 3 D (2100), in comparison with Figure 3 A (current climate), we can see decreases in highly suitable areas in Brazil due to climate change. Projections for suitable areas for *A. palmeri* remain constant worldwide. However, the reduction was more significant in Brazil, Mexico, Australia, and sub-Saharan Africa (Figure 3 B, C, and D).

For the annual analysis of the occurrence of *A. palmeri* using the GIW projected by the CLIMEX model, we highlighted the Brazilian municipalities of Campos de Júlio, Sapezal, Tapurah, and Ipiranga do Norte, Midwest Brazil (Figure 4 and 5A). The GIW model showed growth potential for *A. palmeri* throughout the year, with a sharp decline in the driest months from July to August (Figure 5 A and B).

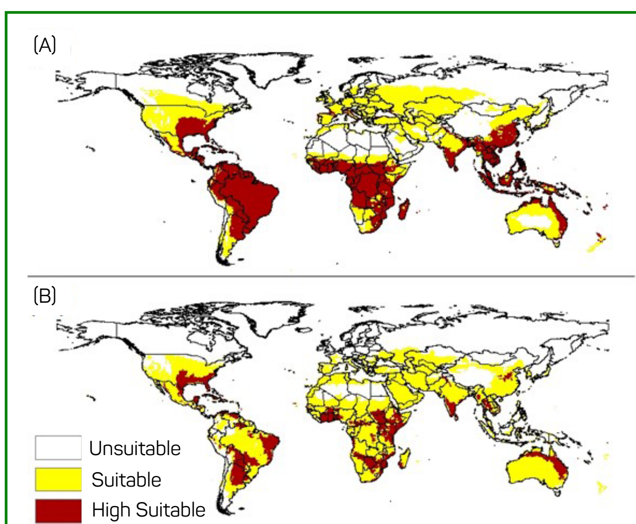

Figure 2 - (A) New model for *Amaranthus palmeri* and (B) Model proposed by Kistner and Hatfield (2018) for the current climate

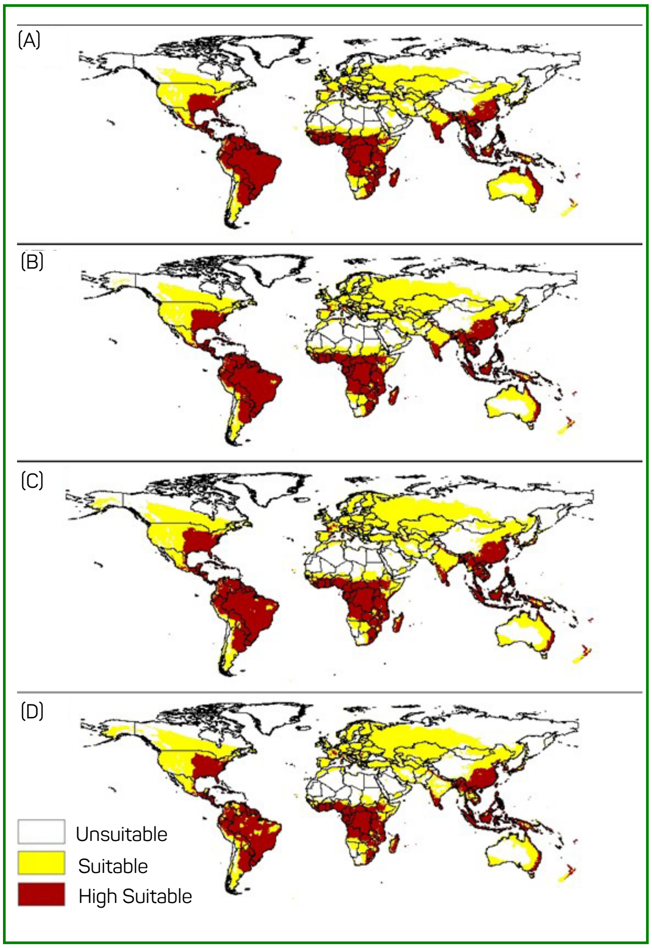

Figure 3 - Potential distribution of *Amaranthus palmeri* for current climate (A) and 2050 (B), 2070 (C), and 2100 (D) climate change in the world

Our sensitivity analysis results showed that five parameters, that is, SM2, SM3, DV0, DV1, and TTHS, were more sensitive to *A. palmeri* because they showed an increase or decrease in area using the higher or lower values proposed by the CLIMEX software (Figure 6). Considering the change in area for each suitability class, that is, unsuitable, suitable, and highly suitable, we observed that some more sensitive parameters had a greater effect on the potential distribution of weeds.

Soil moisture, SM3, and DV0 were more sensitive to changes in suitable areas, whereas SM2, SM3, DV0, and TTHS were more sensitive to changes in the areas that were highly suitable (Figure 6 B and C). For unsuitable areas, changing DV0 and TTHS had a greater influence on the model (Figure 6 A). DV0 and DV1 were the parameters most sensitive to temperature in areas suitable for *A. palmeri*. As for stress rates only for the TTHS, we observed greater sensitivity in the unsuitable, suitable, and highly suitable areas (Figure 6).

4. Discussion

Brazil is divided to by the Tropic of Capricorn; 92% of the territory is in the intertropical zone, and the remaining 8% is in the southern temperate zone (Kandir, 1995). Owing to the territorial extension of Brazil, several climatic conditions can be observed, including equatorial, tropical, highly tropical, humid tropical, semi-arid, and subtropical (Pommer, Barbosa, 2009).

Amaranthus palmeri is an aggressive weed that can rapidly adapt to different environments. Adaptability of this weed has been shown in the United States and

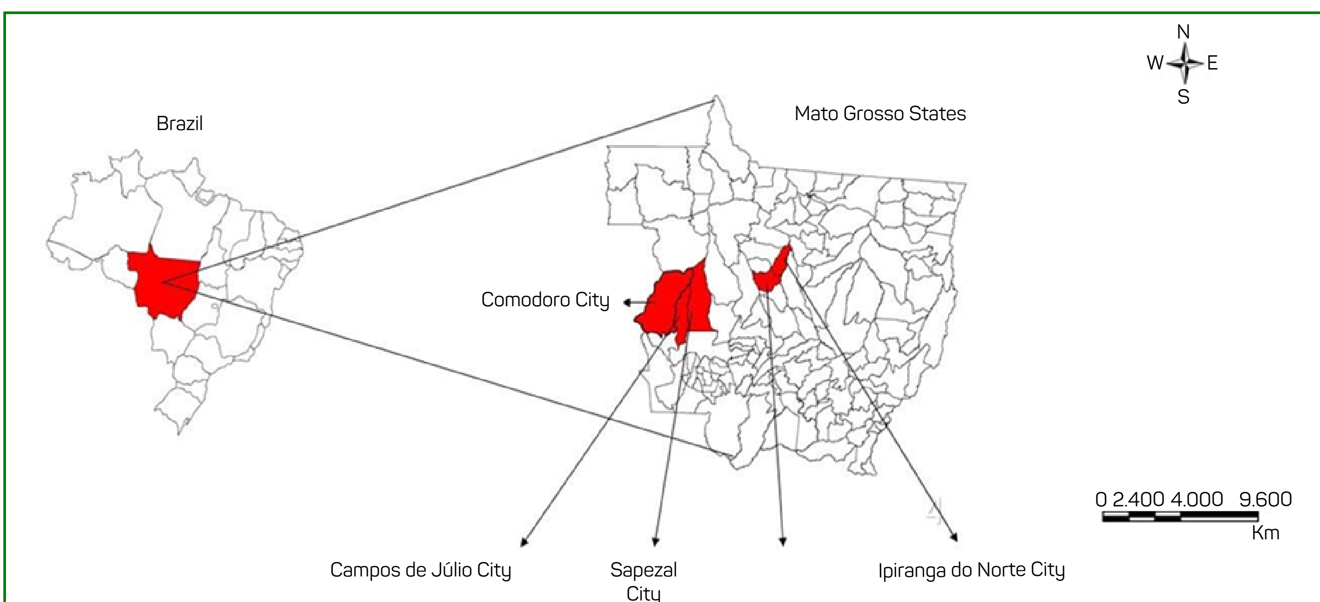

Figure 4 - Map of the Brazilian cities with species (Campos de Júlio, Sapezal, Tapurah, and Ipiranga do Norte) and the municipality where the meteorological data came from

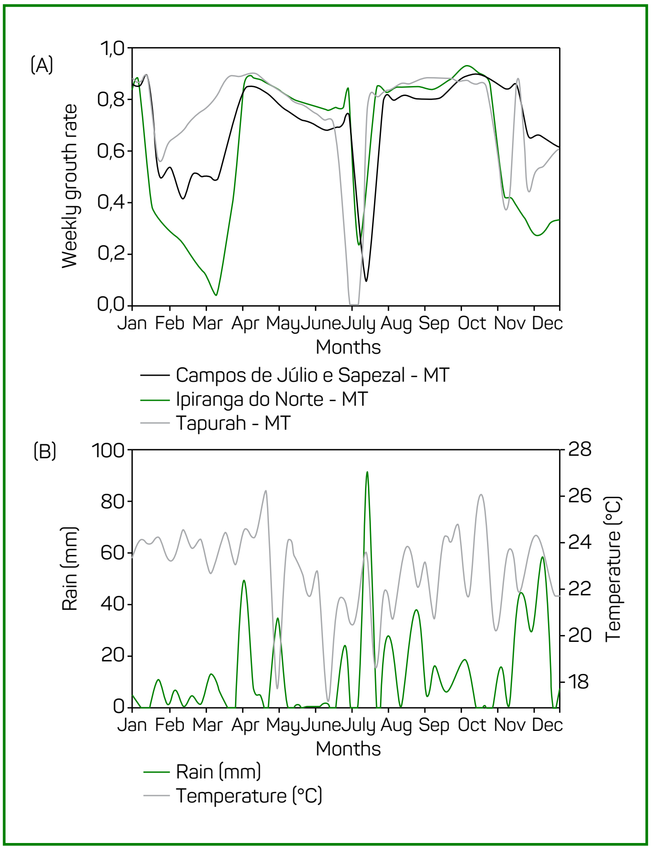

Figure 5 - (A) Weekly growth index (GIW) of *Amaranthus palmeri* in the municipalities of Campos de Júlio, Sapezal, Ipiranga do Norte, and Tapurah, state of Mato Grosso. (B) Precipitation and temperature index for these locations

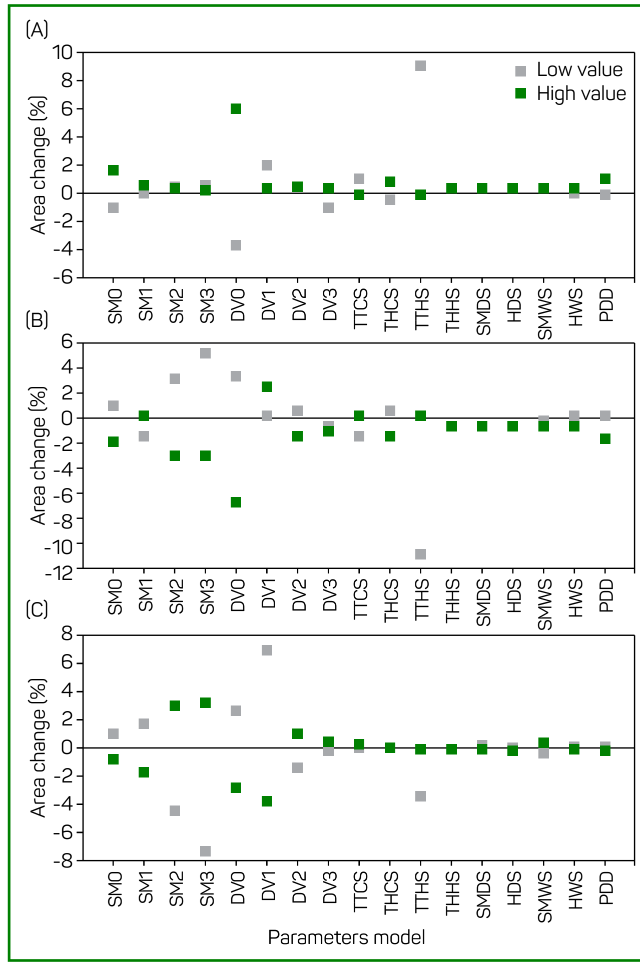

Figure 6 - Changes in (A) unsuitable, (B) suitable, and (C) highly suitable areas for the potential distribution of *Amaranthus palmeri* when the sensitivity analysis was performed based on 17 CLIMEX parameters, with greater sensitivity in EI. The values for the various parameters used are those given in Table 1

Argentina. This species grows in environments where the temperatures are below the ideal temperatures for growth (Tuesca et al., 2016; Steckel, 2007). However, owing to the physiological evolution of C4 metabolism, *A. palmeri* has adapted to tropical environments with high radiation and temperatures, such as Brazil (Ward et al., 2013). The adaptability of *A. palmeri* may be related to its dioecious nature, which favors crossing and genetic diversity (Ward et al., 2013). These characteristics contribute to the rapid adaptation of this species to new environments.

We developed a potential distribution model for the current climate that identified favorable areas for *A. palmeri* (Figure 2 A). These changes occurred in the northern and midwestern regions of Brazil. The greater suitability of these environments for *A. palmeri* may be related to changes in the water balance in these regions. Temperature is not a limiting factor in these regions. Therefore, it can be inferred that the key factor for the adequacy of areas for *A. palmeri* in the Brazilian territory is mainly related to the increase in temperature (2.1 °C) and decrease in precipitation (14%) predicted by the model until 2100 (Suppiah et al., 2007; Chiew et al., 2009).

Kistner and Hatfield (2018) evaluated the potential distribution of *A. palmeri* under current and future climate conditions and observed an increase in climate suitability in the Northern Hemisphere. According to these authors, this change can be attributed mainly to the increase in temperature, which favors the establishment and potential for expansion. In contrast, in the Southern Hemisphere, there was no difference between future climate scenarios and current climate conditions. According to the authors, the model used (CNRM-CM5) indicated a significant decrease in climate suitability in Mato Grosso, Brazil because of cumulative hot-humid stress values above 100, which is the CLIMEX limit for lethal conditions. However, the results obtained using our model differed from those reported by Kistner and Hatfield (2018). Our results have indicated that environmental conditions such as temperature and humidity do not cause lethal stress to *A. palmeri*. This divergence can be attributed to the better fit of the model with the new values, which represents a more robust model and allows for clear alignment with the recent occurrence of *A. palmeri* in the model proposed by Kistner and Hatfield (2018) (Figure 2).

In the weekly growth model (Figure 5 A), better climatic conditions were observed for *A. palmeri* during periods of higher relative humidity. Iamonico and Mokni (2017) have reported similar conditions for the development of *A. palmeri*. However, higher growth rates associated with periods of higher rainfall do not indicate that *A. palmeri* is adapted to soggy or excessively humid soils. The state of Mato Grosso is characterized by a predominance of oxisols with medium texture (Seplan, 2003). This type of soil is generally characterized by a high rate of soil water infiltration (Vilarinho et al., 2013). The higher average temperatures during the day contributed to soil water evaporation. Therefore, the environment during the rainy season was found to be favorable for the development of weeds, which are important in the context of agriculture. June to September is characterized by low rainfall, high temperatures, and a low amount of soil water availabilty (Sotta et al., 2017).

Amaranthus palmeri has been classified as a quarantine weed. Therefore, a series of restrictions are imposed for control. Graphics were prepared based on field observations made during the inspection of infested areas in Mato Grosso (Figures 4 and 5). It is important to note that the field observations generated graphs of growth rates. The space-time growth index was calculated using the method proposed by Kriticos et al. (2015) and the results were based only on climate and did not consider non-climatic factors, such as the occurrence of pests, diseases, soil types, and biotic interactions. However, our GIW results for *A. palmeri* indicate the potential for new approaches to understanding seasonal variations in climatic conditions.

The weekly growth rate of *A. palmeri* is one of the main factors contributing to the control of this weed. Plants can grow between 2.5 cm and 4 cm per day under ideal conditions, making post-emergence herbicide application extremely difficult (Sellers et al., 2003). In Brazil, there are reports of growth up to 6 cm/d (Gazziero, Silva, 2017).

Future climate impact analysis using the CSIRO-Mk3.0 Global Climate model and the A1B scenario resulted in variation in the potential distribution of *A. palmeri* worldwide. With predicted climate change, the potential areas for *A. palmeri* may vary across territorial regions. The projections indicated that areas more suitable for *A. palmeri* above the equator. However, in the short-term (2050 and 2070), regions with high climate suitability remained constant and declined until 2100.

In the long term (2100), the results of this study showed a moderate increase in areas with climatic suitability for *A. palmeri* in countries of the Northern Hemisphere (Figures 3 B, C, and D). With climate change, an increase in the number of potentially suitable areas in cold regions is expected (Bourdôt et al., 2012). Canada, Russia, and the United States stand out for the expansion of new areas suitable for *A. palmeri*. However, countries in the Southern Hemisphere, such as Brazil, Australia, and Africa, will have reduced areas that are highly suitable for this weed. This reduction in areas with high suitability has mainly occurred in the tropical and subtropical regions. With climate change, high temperatures may cause for *A. palmeri* thermal stress (Burkett et al., 2014). In spatial distribution studies, uncertainties are related to the impact of climate change (Taylor, Kumar, 2012). Many plant species respond differently to climate-related evolutionary and adaptive processes (Franks et al., 2007).

The results of the sensitivity analysis showed that the upper soil moisture threshold (SM3), lower threshold temperature (DV0), lower optimum temperature (DV1), and TTHS were the most sensitive parameters in the suitable and highly suitable area categories (Figures 6 B and C). SM3 (upper soil moisture threshold) defines the upper soil moisture; when a higher value was used for the adjustment, there were increases in highly suitable areas. In contrast, when we used a lower value of this parameter, there was a decrease in highly suitable areas (Figure 6 C). With a change in the TTHS, we obtained greater variation in the suitable and highly suitable areas. We should emphasize that *A. palmeri* may be associated with regions with high temperatures and soils with high humidity (Ward et al., 2013; Iamonico and Mokni, 2017). Thus, the sensitivity of soil moisture and heat stress temperature threshold parameters to the potential distribution of *A. palmeri* were evident. Sensitivity analysis is a useful tool for researchers and farmers because it provides knowledge of the parameters that can influence the occurrence of a given species (Silva et al., 2020).

The current and future suitable area models represent a risk-warning system for Brazil. In addition to its economic impacts, the spread of *A. palmeri* can cause ecological problems. Because it is highly competitive, this weed can affect biomes such as the Amazon, resulting in biodiversity loss. Further research is needed to investigate the effects of soil type, the incidence of pests and diseases, and biotic interactions on the developmental potential of this weed. Given the adaptability of *A. palmeri* and the extent of damage it can cause, the monitoring, containment, and eradication (control with the use of herbicides, and machines with *A. palmeri* seeds) of this species in areas at risk of invasion is of fundamental importance. Preventive dissemination measures in new areas and duly implemented eradication strategies are important for the proper management of this pest.

5. Conclusion

For the current climate, our model identified regions with favorable climatic suitability for *A. palmeri* on most continents. Tropical and subtropical zones in northeastern and western Australia are currently experiencing a reduction in areas that are suitable under climate change. Temperate zone sites have potential areas of expansion for *A. palmeri* in the northern USA, Russia, and China under climate change conditions. In Brazil, there has been a decrease in suitable areas for the long term (2100), especially in the Midwest and Northeast regions.

Using ecological niche models, it is possible to analyze the risks to the Brazilian agricultural economy of *A. palmeri*. These results enable the identification of places with a greater need for preventive phytosanitary measures against *A. palmeri*, such as Mato Grosso.

Authors' contributions

SRF, FHVA, JBS, AFS, ORS, and RSS: conceptualization of the manuscript and development of the methodology. SRF, FHVA, JCBS, JBS, AFS, RSR, and RSS: execution of the experiments. SRF, FHVA, JCBS, ACB, JBS, AFS, RSS, and ORS: data collection and curation. SRF, FHVA, JCBS, JBS, AFS, ORS, and RSS: data analysis. SRF, and FHVA: data interpretation. JBS, AFS, and RSR: funding acquisition and resources. SRF, FHVA, JCBS, JBS, AFS, ORS, and RSS: project administration. JBS, AFS, ORS, and RSS: supervision. SRF, FHVA, and RSS: writing the original draft of the manuscript. SRF, FHVA, ACB, JCBS, JBS, AFS, RSS, and ORS: writing, review, and editing.

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