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RESEARCH ARTICLE

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Climatic zoning of chia (*Salvia hispanica* L.) in Chile using a species distribution model

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Abstract

Salvia hispanica L., known as chia, is a plant species originally from tropical and subtropical Mesoamerica. It is economically important because its seeds produce omega-3, thus its demand has increased in Chile and internationally. As there is no commercial production in Chile, we investigated the places in the country where this species could be cultivated in order to satisfy at the least the national demand. The aim of the study was to quantify the main climatic requirements of chia and to produce a climatic aptitude map for chia cultivation in Chile. The methodology was based on the Maxent species distribution model. We used 78 georeferenced data points where chia is grown throughout the world, mostly from the GBIF database, along with raster climatic layers from the Worldclim project. We estimated the performance curves of annual precipitation and temperature along with their respective optimal and critical values, in analogy with the Ecocrop method. The maps used two scenarios for crops in different conditions, with and without irrigation. The results indicated that the intermediate depression and coastal edge of mainly the Arica y Parinacota, Tarapacá, Antofagasta and Atacama regions have optimum conditions for irrigated crops, but it would be impossible in rainfed conditions. We conclude that chia's cultivation niche is reduced due to its tropical climate requirements; however, it can be cultivated under irrigation in northern Chile.

Additional keywords: functional food; performance curves; suitability, Maxent.

Abbreviations used: AUC (area under the curve); C_n (critical minimum value); C_x (critical maximum value); GBIF (Global Biodiversity Information Facility); O_n (optimal minimum value); O_x (optimal maximum value); PP (probability of presence); ROC (receiver operating characteristic); SDM (species distribution model) Tnc (minimum temperature of the coldest month); Tnw (minimum temperature of the warmest month); Txc (maximum temperature of the coldest month); Txw (maximum temperature of the warmest month).

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Introduction

Salvia hispanica L., whose common name is chia, is a summer annual herb of the Lamiaceae native to Mesoamerica (Ayerza & Coates, 2006; Cornejo & Ibarra, 2011). Chia is an interesting crop mainly due to its nutritional richness, both the high antioxidant content of the leaves and the essential fatty acids (omega-3) in its seeds. It is considered a functional food with an important economic potential in the food industry (Muñoz *et al.*, 2013). Given these characteristics, the demand for chia seeds has increased internationally, thus its cultivation has extended beyond its native tropical habitat (Ali *et al.*, 2012).

The case of Chile is no exception, where the demand reached 645 tons in 2011; however, there is still no local commercial production in this country (De Kartzow, 2013). Hence growing this crop in Chile could satisfy its increasing national demand. Moreover, this plant was chosen to be grown in Chile because it is able to grow under limited water conditions and is resistant to drought, considering climate change threats in agriculture (Ayerza & Coates, 2006; Fereres *et al.*, 2011; Ramírez & Lozano, 2015).

In order to cultivate chia in Chile, a crop zoning is required to predict its aptitude in different areas to ensure the success of investment and production. Considering that among natural factors climate is the one that most affects plant development (Baginsky *et al.*, 2016), we defined a climatic zoning to determine the territorial pattern of aptitude for chia cultivation. Yield data for the species according to environmental variables is required to do this type of zoning, such as that defined by Ecocrop (2007), but this information has not been published for chia.

Nowadays there are several cartographic representations called Species Distribution Models (SDM), which can predict the suitability of an area for the adaptation of a species as a function of the variables used to generate it, *e.g.* BIOCLIM, DOMAIN, GARP and others (Guisan & Zimmermann, 2000; Elith *et al.*, 2006; Soberón, 2011). However, we chose the Maxent model (Phillips *et al.*, 2006) because it has the most efficient results using few presence data (Elith *et al.*, 2011), and it is able to project a realized niche in a territory where there is no presence of the species.

The objectives of this study were to identify the main climate requirements of chia, then to use this information to generate a map of climatic aptitude for its cultivation in Chile. Thus this study was based on the ecophysiology of chia. We estimated the environmental requirements of the species in its native habitat and where it is grown, and projected these requirements onto a new territory. This was performed using an SDM, also called the ecological niche model, which estimated the potential distribution of the species in the entire territory of Chile based on bioclimatic variables (Hijmans *et al.*, 2005).

Material and methods

Study area

The study area was continental Chile. This territory extends from 17.5° to 56° S latitude, with an elevation range from sea level to over 6000 m. Its topography may be divided into four characteristic zones, roughly from east to west: the Andes Range, the Intermediate Depression, the Coast Range and the littoral flatlands, thus this territory includes a broad range of climates and vegetation. It is divided into 15 administrative regions.

Environmental variables

We used only climatic grids for this study, which were downloaded from the WorldClim database (http://www.worldclim.org) at a spatial resolution of 2.5 arc-min, about 4.63 km at the equator (Fourcade *et al.*, 2014). This continuous grid format must be transformed to ASCII format in the ArcGis 10 software (ESRI, 2012) to use it in Maxent. Variables such as altitude, slope and exposition were not used for the model, since the layers of Worldclim (Hijmans *et al.*, 2005) were constructed using altitude, thus avoiding the problem of spatial autocorrelation (Legendre, 1993). Ayerza (2009) suggested that the length of the growth cycle was related to temperature and not to altitude, and Martínez *et al.* (2012) indicated that the areas closest to sea level are the warmest, and temperature decreases with increase in elevation.

We used the environmental layers of extreme temperatures (maximum and minimum of the coldest and warmest months) and the mean annual precipitation from the Worldclim project (Hijmans *et al.*, 2005) to calculate the main climatic requirements. We selected variables from the 19 bioclimatic variables of Worldclim (Hijmans *et al.*, 2005) for the models that produced the aptitude map; these are the most often used predefined bioclimatic variables available in the Worldclim global database of climate surfaces (Hijmans *et al.*, 2005; Pliscoff & Fuentes, 2011; Duarte *et al.*, 2014; Peña *et al.*, 2014). These variables are: annual mean temperature (Bio1); mean monthly temperature range (Bio2); isothermality (Bio3); temperature seasonality (Bio4); maximum temperature of warmest month (Bio5); minimum temperature of coldest month (Bio6); temperature annual range (Bio7); mean temperature of wettest quarter (Bio8), mean temperature of driest quarter (Bio9), mean temperature of warmest quarter (Bio10); mean temperature of coldest quarter (Bio11); annual precipitation (Bio12); precipitation in wettest month (Bio13); precipitation in driest month (Bio14); precipitation seasonality (Bio15); precipitation in wettest quarter (Bio16); precipitation in driest quarter (Bio17); precipitation in warmest quarter (Bio18) and precipitation in coldest quarter (Bio19). The variable selection was made using the Pearson correlation matrix in the ENMTools software version 1.3 (Warren *et al.*, 2008), considering as significant those variables with $r>0.65$, as recommended by Phillips *et al.* (2006). This selection was made to avoid spatial autocorrelation (Legendre, 1993) and to avoid overfitting errors in the model.

Occurrence data

After eliminating duplicated points, occurrences were selected so that there was no more than one point in each pixel of the environmental layer grid, thus avoiding spatial autocorrelation (Legendre, 1993). These filtering processes were performed using Microsoft Excel and ArcGis 10 (ESRI, 2012). We compiled 78 records of presence (occurrence) of chia around the world to perform the modeling. Sixty of these points were located in its native range and were obtained from GBIF (2015); the other 18 points were locations where it is grown without irrigation outside its native range, and were obtained from the studies of Ayerza and Coates (Coates & Ayerza, 1996, 1998; Ayerza & Coates, 2004; Ayerza, 2009, 2010, 2013), the Virtual Herbarium of Australia (AVH, 2015) and GBIF (2015) (Fig. 1).

Species distribution model

The spatial modeling of the SDM was generated with the Maxent version 3.3.3k software (Phillips *et al.*, 2006), which creates a statistical model that estimates the probability distribution of maximum entropy. The result is interpreted as the environmental suitability of an area for a species to develop, which has also been called the probability of presence. For every scenario we always generated a pair of species distribution models with the same 2.5 arc min spatial resolution but different extension, the native range and the world range, in order to search for greater niche breadth in the model. The background of the native range model was limited to the territory of the countries of Mexico, Guatemala, Belize, El Salvador, Honduras, Nicaragua and Costa Rica. The occurrence points were divided randomly, 75% to create the model and 25% to validate it. The mean of each model was estimated with 50 bootstrap replicates. Although Phillips *et al.* (2006) recommended leaving the default quantity of pseudo-absences, we modified them in this study since different ranges were used for the models. For the native range model we tested 600 (10 x presences), 2000, 5000 and 10,000 pseudo-absences, and for the world range we tested with 780 (10 x presences), 2000, 5000 and 10,000 pseudo-absences. The number of pseudo-absences was calibrated for each model using two evaluation criteria, the area under the ROC (receiver operating characteristic) curve, called area under the curve (AUC), and the omission test. We used the AUC because it is the one most used by other authors, in spite of the criticisms it has received. One of the problems associated with the use of ROC curves is that there must be true absence data, which generates an error since the abscissa of the graph would only be the proportion of area predicted by the model. Another problem is that the method assigns the same weight to errors of omission and commission; however, omission errors are more important because they are areas that the model is incapable of predicting, which might be important for the survival of the species (Mateo *et al.*, 2011). The value of the AUC is among the results of Maxent for each model and it was interpreted

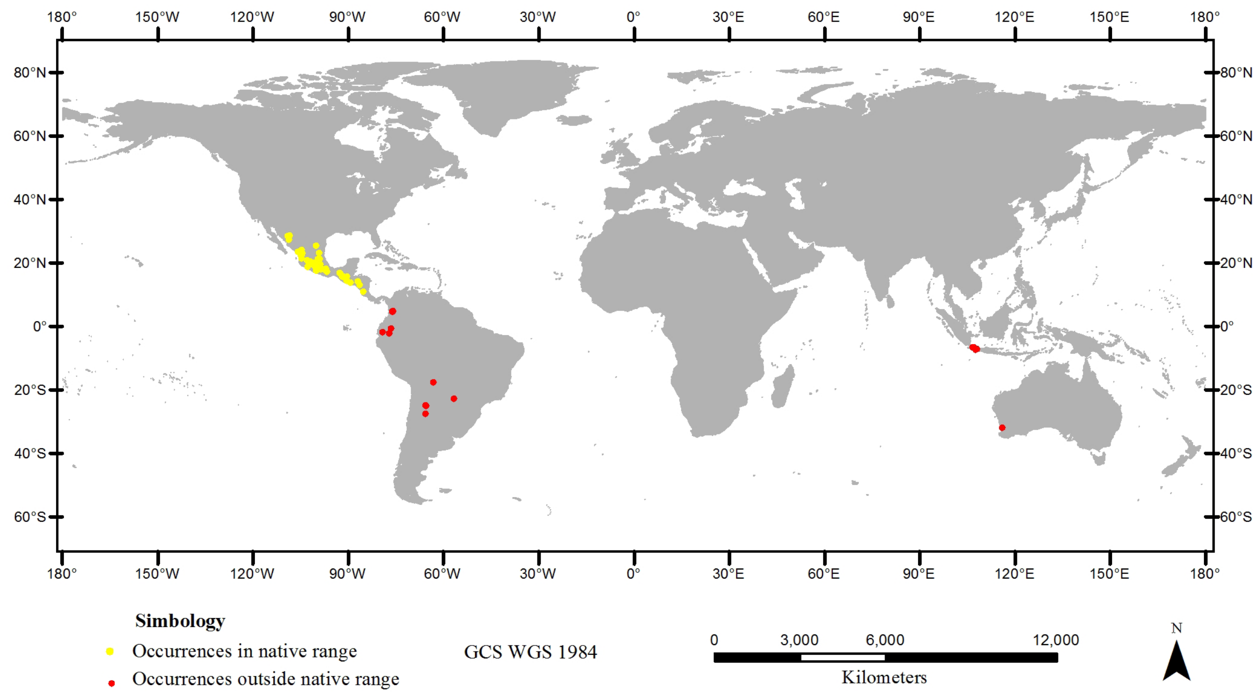

Figure 1. Occurrences of *Salvia hispanica* utilized for the species distribution model (SDM).

using the recommendation of Swets (1988): < 0.6 bad; 0.6-0.7 poor; 0.7-0.8 acceptable; 0.8-0.9 good, >0.9 excellent. The omission test was performed using the 10% cutoff point returned by Maxent with the ArcGis 10 software (ESRI, 2012). The rest of the configuration used the default values as recommended by its authors (Phillips *et al.*, 2006).

Main climatic requirements of chia

The climatic requirements of the crop were defined using performance curves, which indicate the performance of a species according to each environmental variable considered; these are analogous to thermal performance curves (Schulte *et al.*, 2011). They identify the range of values for each variable in which the species can survive and the range in which it develops ideally, as Ecocrop (2007) has determined for more than 2300 plant species. This may also be interpreted as the search for the tolerance of the species to different environmental variables, since these tolerance limits define the spatial limits of distribution. Growth and reproduction are limited when the abiotic variables are near the tolerance limit, which is directly related to the abundance and production yield of the species (Richards & Janes, 2011). Performance may be measured in different ways, including survival, reproductive success and fitness (Pianka, 2011), however these are empirical measures. Performance is optimized in the optimal range, between the minimum and maximum optimal values (O_n and O_x), while it declines to 0 at the critical minimum and maximum values (C_n and C_x) which define the tolerance range (Fig. 2A).

The Maxent software generates response curves after creating an SDM, which are associated with the performance curves of a species. As response curves are *a priori* estimations, they substitute performance for probability of presence (Morales *et al.*, 2015). The performance curves were defined for two variables, temperature and precipitation, similar to the Ecocrop (2007) definition and considering the dependence of crops on these variables. Temperature determines the overall effect on growth (Fernández & Johnston, 2006); the growth and development of a plant occurs within a framework of temperatures in which below the minimum it does not grow, it grows at a maximum rate with the optimal temperature and does not grow and may die at above the maximum temperature (Salisbury & Ross, 2000; Vidal, 2009). Water is fundamental for plant growth, since without it there is no photosynthesis or nutrient transport. Scarcity of water decreases both yield and the quantity and quality of production, while an excess does not allow the roots to respire (Martínez *et al.*, 2012).

Using the response curves returned by Maxent we calculated the values for each environmental variable independently of the others, using the value of 0.5 for probability of presence (PP). Since Maxent returned probability values less than 1 even within its native area, the values were normalized by the

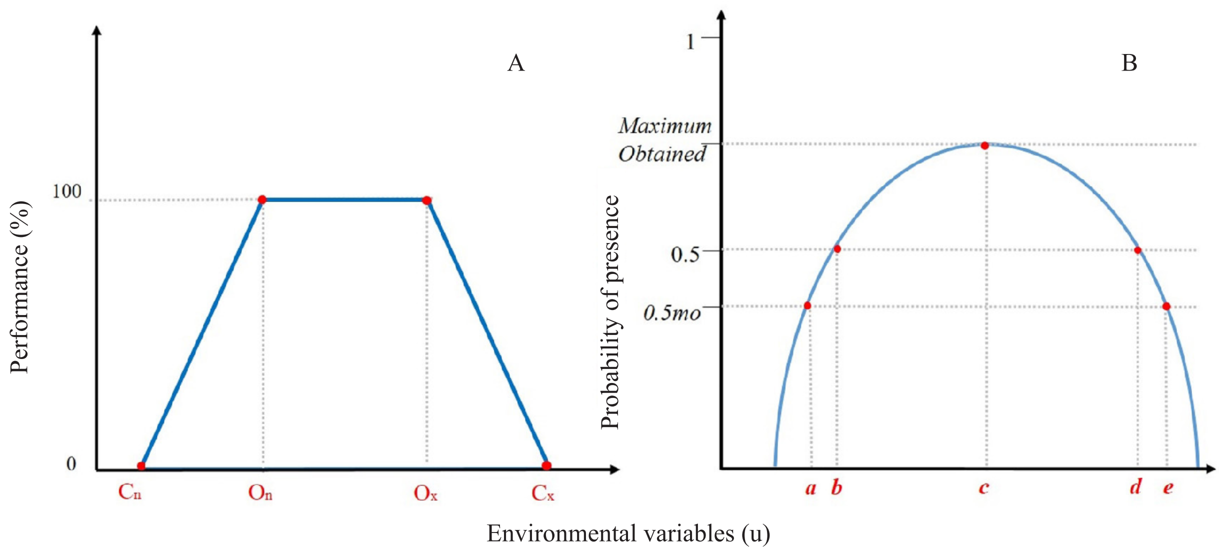

Figure 2. Simplified approximation of performance curve and response curve from Maxent. In this figure, A is the performance curve, where C_n is minimum critical value, O_n the minimum optimal value, O_x is the maximum optimal value and C_x is the maximum critical value; B is the response curve of Maxent, with the proposed analysis values (*a, b, c, d, e*).

maximum value, thus the current rule was applied to the adjusted probabilities. Using these criteria, we defined analysis parameters *a-e* from properties of the curve (Fig. 2B): *a* is the variable value with 0.5 PP adjusted and before maximum; *b* is the variable value with 0.5 PP before the maximum; *c* is the value of the variable at maximum probability of presence; *d* is the value of the variable with 0.5 PP above the maximum and *e* is value of the variable with 0.5 PP adjusted and above the maximum. With these five values we obtained the mean between the analogous pairs according to the two extension models. For the temperature variables we calculated the mean of the values *a* and *b*, and the mean of *d* and *e*. Finally, the performance curves were defined using these ranges.

Climatic suitability cartography of chia in Chile

Using the selected bioclimatic layers along with the described occurrences and the Maxent configuration described we generated 2 SDM scenarios; scenario A with precipitation and temperature layers and scenario B with only temperature layers, both worldwide. Scenario A corresponds to cultivation without irrigation, and scenario B to cultivation with irrigation so precipitation is not a limiting factor. To extend the models to Chile we configured the software with a projection to the Chilean territory, with the layers also entered in ASCII format with 2.5 arc min resolution and processed in ArcGis 10 (ESRI, 2012). The importance of the model variables was tested using Tukey's jackknife (Phillips *et al.*, 2011). Once the model was chosen based on the parameter calibration, the suitability values returned by Maxent were classified for the Chilean territory analogously with the aptitude classes of the Agro-Ecological Zoning of crops (AEZ) proposed by FAO (1996), which are: 0-0.2 "not suitable"; 0.2-0.4 "marginally suitable"; 0.4-0.6 "moderately suitable"; 0.6-0.8 "suitable"; 0.8-1 "very suitable". Finally, we generated the corresponding maps in the ArcGis 10 software (ESRI, 2012).

Results

Main climatic requirements of chia

Calibration and evaluation of the models. To obtain the response curves from Maxent we produced two models of different extension, the native range and worldwide. The number of pseudo-absences was defined as 50,000 for the worldwide model and 5000 for the native model, according to the results of the AUC and the omission test. The best AUC (0.977) was given for the world model, considered as an excellent model, with 8.9% omission (7 points). The chosen native model had an AUC of 0.928, also considered excellent, with 11.7% omission (7 points).

Precipitation performance curve. The maximum probability of presence for annual precipitation was 0.6 for both models according to the response curves, which corresponds to approximately 1000 mm/yr (*c* analysis value). The critical and optimal values for annual precipitation were obtained directly from the proposed analysis values, in which *a* generated the value C_n, 660 mm/yr, *b* produced the value O_n with 780 mm/yr, *d* generated the value O_x with 1560 mm/yr and *e* produced C_x with 2130 mm/yr (Fig. 3A).

Temperature performance curve. The maximum probability of presence for the four variables was between 0.6 and 0.7, for both the native and world models. The minimum temperature of the coldest month (Tnc) was excluded from the results because it included very low values, incompatible with the intolerance of the species to frosts. The critical and optimal values were thus defined with the *a-b* and *d-e* means of the variables maximum temperature of the coldest month (Txc), minimum temperature of the warmest month (Tnw) and maximum temperature of the warmest month (Txw). The temperature value of C_n was defined with the *a-b* mean of Txc and was 10° C. O_n was defined with the *d-e* mean of Txc; it coincided with the *a-b* means of Tnw and Txw, which confirmed the value of O_n. Thus the minimum optimum (O_n) was estimated to be 18 °C. The O_x value for chia was defined as the *d-e* mean of Tnw, which was 26 °C. The maximum critical temperature was estimated as the *d-e* mean of Txw, which was 29 °C (Fig. 3BCDE).

Climatic suitability map

Scenario definitions. The bioclimatic variables to generate the SDM of chia were selected as the least correlated variables; these were Bio1 (annual mean temperature), Bio2 (mean diurnal range), Bio4 (temperature seasonality), Bio 12 (annual precipitation) and Bio15 (precipitation seasonality). Thus scenario A was composed of these five variables, while scenario B considered only the temperature variables Bio1, Bio2 and Bio4.

Evaluation and calibration of the models. Models of scenarios A and B were both classified as excellent with an AUC of 0.97, while the omission test indicated 8.9% of the points omitted (7 points) for both models. Pseudo-absences were established

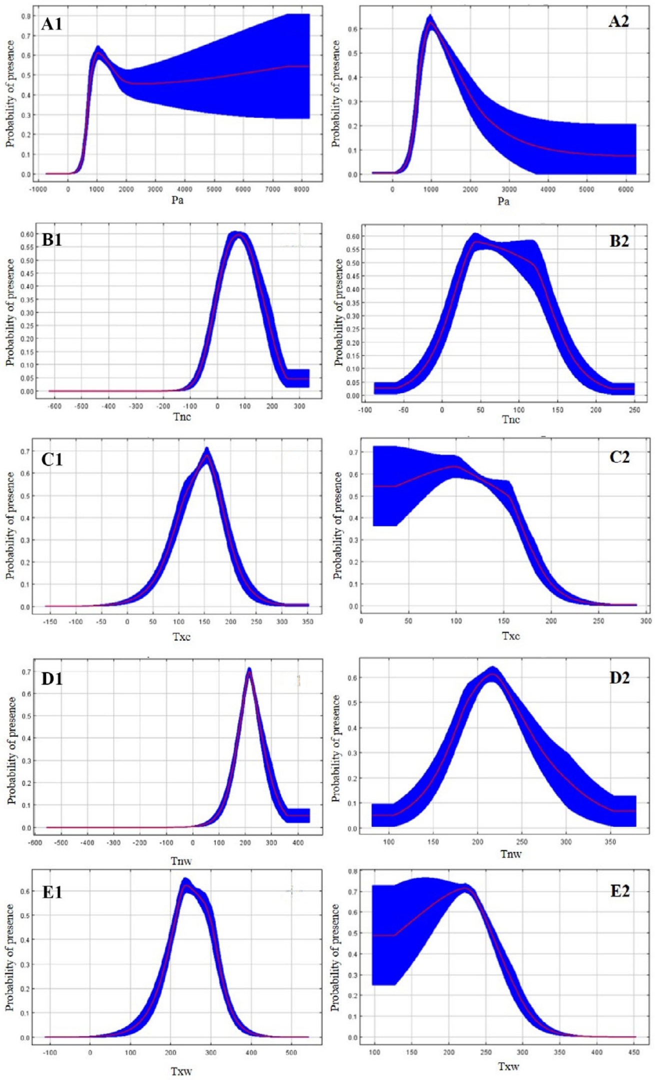

Figure 3. Response curves of the probability distributions generated by Maxent. In this figure, A is the annual precipitation (Pa), B is minimum temperature of the coldest month (Tnc); C is the maximum temperature of the coldest month (Txc); D is the minimum temperature of the warmest month (Tnw) and E is the maximum temperature of the warmest month (Txw). Number 1 indicates the world response curves, while 2 indicates the native area curves.

as 50,000 according to the AUC obtained. The jackknife test of the SDM of scenario A showed that annual mean temperature (Bio1) was the variable that contributed most. The order of the contribution of the other variables was Bio4, Bio12, Bio15; the variable that contributed least was Bio2. However, the set of variables produced a much better model than any variable by itself. The same order of contribution of the temperature variables was found for scenario B.

World SDM. The climate envelope for scenario A shows aptitude zones in equivalent latitudes for both hemispheres, located at or near the Tropics of Cancer and Capricorn (23° 26’ 14’’ in both hemispheres). This confirms the exclusively tropical nature of the species. It also shows that the potential distribution according to this realized niche model is quite restricted, which explains why the species is not found globally. The model showed a maximum presence probability of 0.94 (Fig. 4A). It must be noted that for this scenario there are other countries besides Guatemala and Mexico that have a high presence probability of the species (>0.6), including Bolivia, Peru, Ecuador, Colombia, Kenya, Angola,

Table 1. Area (km²) by suitability category for chia cultivation in Chile under irrigation.

Region	Very suitable	Suitable	Moderately suitable	Marginally suitable	Not suitable	Total
Arica y Parinacota (XV)	-	4468.08	3109.15	3338.68	5736.48	16652.39
Tarapacá (I)	-	7111.80	19796.46	5654.68	10028.03	42590.96
Antofagasta (II)	11498.93	38719.36	38340.17	18165.85	19895.14	126619.45
Atacama (III)	57.83	7994.20	23963.32	19049.39	24631.02	75695.76
Coquimbo (IV)	-	-	11343.48	13936.23	15549.52	40829.23
Valparaíso (V)	-	252.38	8238.27	3705.22	4125.27	16321.14
Metropolitana (RM)	-	-	1184.98	7641.66	6531.23	15357.82
O'Higgins (VI)	-	-	-	8546.64	7740.69	16287.33
Maule (VII)	-	-	435.83	15700.58	14121.39	30257.80
Biobío (VIII)	-	-	1377.50	19982.78	15615.44	36975.71
La Araucanía (IX)	-	-	-	15484.04	16166.49	31650.53
Los Ríos (XIV)	-	-	-	5592.63	12589.71	18182.34
Los Lagos (X)	-	-	-	522.52	47502.39	48024.92
Aisén (XI)	-	-	-	-	105173.97	105173.97
Magallanes (XII)	-	-	-	-	129311.13	129311.13
Total	11556.76	58545.82	104679.95	137320.89	434717.92	749930.49

Zambia, Zimbabwe, Congo, Ruanda, Burundi, Malawi, Madagascar and particularly Ethiopia, where the presence probabilities are greater than 0.8. In all these countries chia could be grown as a rainfed crop.

Since the precipitation variables were excluded for irrigated cultivation (scenario B), the geographic distribution of the niche covered a wider range than in scenario A, expanding to areas near the tropics in both hemispheres. Model B had a maximum probability of presence of 0.92 (Fig. 4B). The areas with greatest presence probability (>0.6) are places where the species could be cultivated and included the following additional countries: Chile, Venezuela, Brazil, Panama, Costa Rica, Dominican Republic, Honduras, Namibia, South Africa, Tanzania, Democratic Republic of Congo, Uganda, Yemen, Indonesia, Papua New Guinea, India, Vietnam and Kenya, all with presence probabilities above 0.8.

Zoning of climatic suitability in Chile. The projection of the model for scenario A indicated that Chile is not a plausible niche for chia, since in addition to the low probability of presence obtained, the layer of winter precipitation that was included enabled areas where precipitation occurs in winter while temperatures are too low for the plant to develop; this result indicates that rainfed cultivation is not feasible in mainland Chile. The highest climate category was "moderately suitable", mostly in the Maule region; however, this area has frosts, which would impede its development (Fig. 5A).

The zoning for scenario B showed favorable results for agriculture under irrigation. According to this scenario the Chilean territory had a "very suitable" area of 11556.76 km², mostly in the Antofagasta region but also including Atacama. The "suitable" category included an area of 58545.82 km², located in the Arica y Parinacota, Tarapacá, Antofagasta, Atacama and Valparaíso regions. The "moderately suitable" area additionally included the coastal areas of Coquimbo and a large part of Valparaíso region. Table 1 shows the total areas by category of climatic aptitude with irrigation. Note that the category "marginally suitable" was present in 13 of the 15 regions of the country.

Figure 5B shows the map of climatic zoning for chia in Chile with irrigation. Most of the suitable area is located in the littoral plains and intermediate depression of Antofagasta, followed by the Arica y Parinacota and Atacama regions. The Andes Range zone was completely excluded, given the low temperatures in the higher altitude zone. The areas in the "very suitable" and "suitable" categories are mostly located in the northernmost part of Chile, which include the highest temperatures in continental Chile that fulfill the temperature requirements of the species. The "suitable" category also includes a small area in the Valparaíso region, while the "moderately suitable" category includes the entire coastal edge and intermediate depression of the northern part of the country, along with two small areas in the Metropolitan region and two regions farther south, Maule and Bío-Bío.

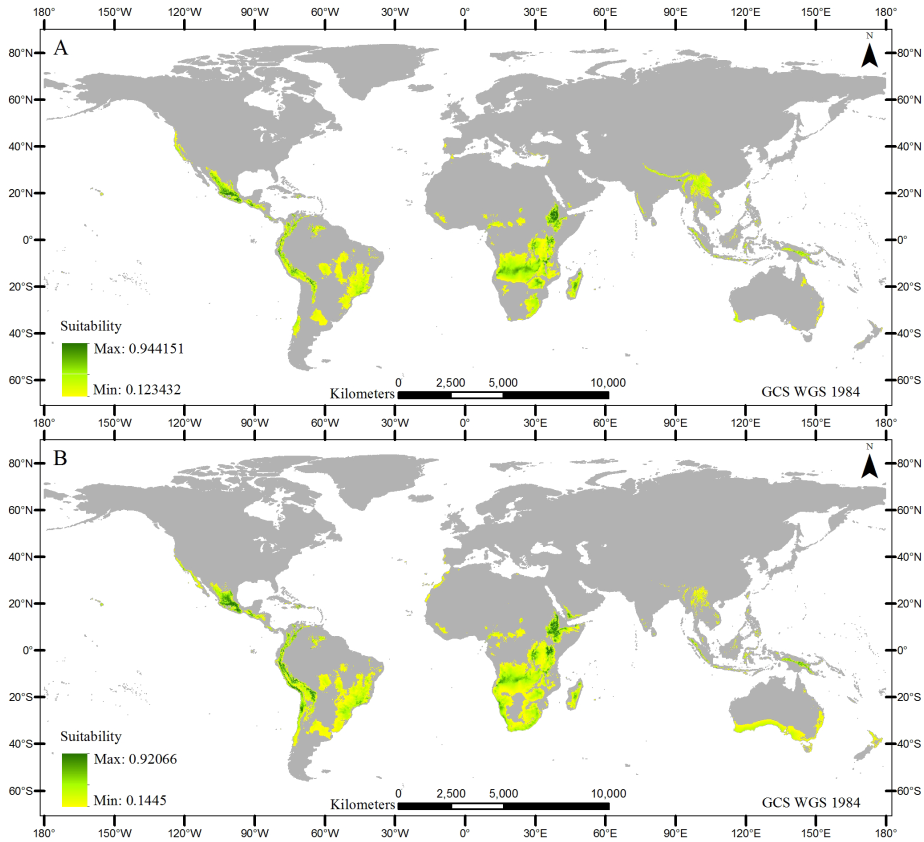

Figure 4. Worldwide cultivation potential distribution of *Salvia hispanica* based on the Maxent model. A, rainfed crop; B, irrigated crop.

Discussion

The minimum critical (C_n) and minimum optimum (O_n) values found here for annual precipitation were very similar to the results of other reports, but this was not the case for the maximum values O_x and C_x. However, the earlier studies were not based on an empirical study, but only on a literature review (Ramírez *et al.*, 2012; Orozco *et al.*, 2014). In relation to other species, chia is most similar to the critical and optimum values of the performance curves of *Amaranthus hypochondriacus*, probably due to a similar original distribution, while *A. caudatus* and *A. cruentus* have wider ranges of tolerance than chia (Ecocrop, 2007).

Since chia has an annual cycle of approximately 150 days (Ayerza & Coates, 2006), the water requirements of the plant must be available during its 5 months of growth; these are different than the amounts available in 12 months which were used for calculations. Also, the crop cycle is different for different varieties; for example, the Acatic variety takes 55 days to flower, while the Guatemala variety takes about 120 days. The distribution of precipitation over the year varies in different areas, thus there is ambiguity in the interpretation if the mean annual precipitation is used for an annual plant. Bendaña (2012) considered chia as a drought-tolerant species, but it requires a minimum of 500 mm precipitation annually to develop its crop. Miranda (2012) indicated that chia cultivation should be established in areas with at least 800-900 mm “well distributed” annual precipitation.

The optimal temperatures we obtained are in full agreement with the optimal ranges reported by Orozco *et al.* (2014) and by Ramírez *et al.* (2012), but differ in the tolerance range, especially in the minimum critical value (C_n), which indicates that these authors did not consider the adaptation of the species outside its native range. Bendaña (2012) reported that chia can resist temperatures down to 12 °C, similar to our results, and estimated that it can withstand up to 32-33 °C. The values we estimated for chia are most similar to *A. hypochondriacus*, since *A. caudatus* and *A. cruentus* tolerate higher temperatures (Ecocrop, 2007).

In closing, the response curves of the environmental variables that the Maxent software returned, in spite of being *a priori* or theoretical estimations, along with the methodology proposed for their analysis may be useful to quantify the requirements of a species. This method is also faster than the empirical

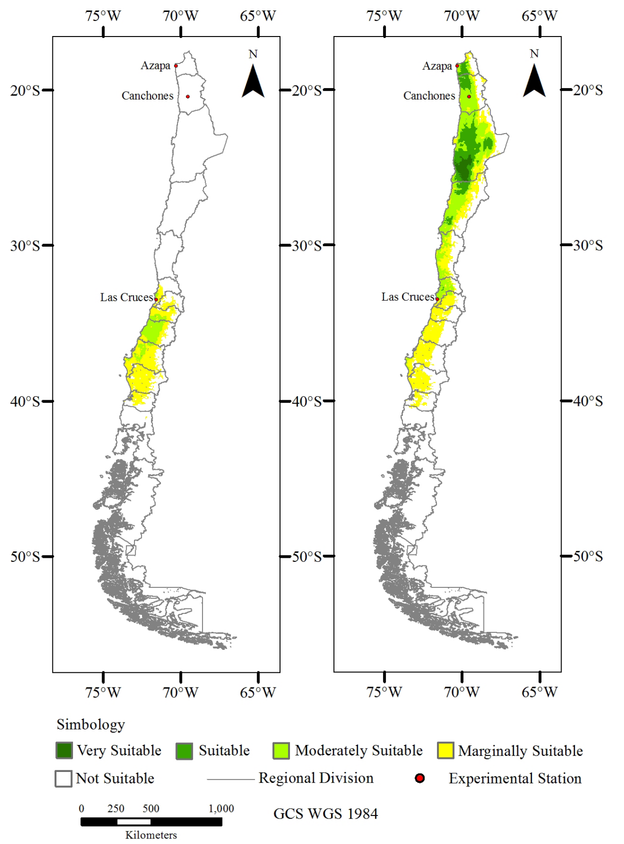

Figure 5. Climate suitability map for *Salvia hispanica* cultivation in Chile derived using the Maxent model. A, rainfed crop; B, irrigated crop.

methods, thus it is recommended if results are required quickly. All the proposed values, both for temperature and precipitation, can only be validated or discounted after the generation of empirical studies of chia under controlled conditions for these variables.

The zoning scenarios were established based on the global availability in public databases of layers with the chosen spatial resolution of 2.5 arc min. Although the photoperiod layer would have been valuable to model the niche of chia, given its sensitivity to the hours of daylight and dark for flowering (Ayerza & Coates, 2006), this information was not available. Layers were also not available for solar radiation, relative humidity, evapotranspiration or soils. In addition to the lack of availability of these layers, the scale of the variables according to the type of niche should also be considered. This study considered the Grinnellian niche, in which climatic and topographic variables are usually used, which correspond to a coarse grid (Soberón, 2007; 2011), while the soil variables, for example, correspond to an Eltonian niche and finer grid, since this entails greater variability in their data. Therefore, it was theoretically not compatible to work with the worldwide Grinnellian niche using Eltonian layers.

According to Schultz (2009), *Salvia* species which are present in Chile (*S. gilliesii, S. paposana, S. rhombifolia, S. tubiflora and S. paposana*) are located in the coastal area of the Antofagasta region, due to the presence of the frequent dense fog in ten different oases. These places were classified into the suitability categories of the climatic zoning for chia to check the agreement of the suitability model with those oases, but they did not agree completely. Only three oases were classified in the "suitable" category (La Plata, Paposo and Matancilla), six oases were classified in the "moderately suitable" category (Tocopilla, Blanco Encalada, Medano, Rinconada, Cerro Perales and Taltal) and one oasis was classified in the "marginally suitable" category ("Miguel Díaz"). This incongruence may be due to the spatial resolution chosen for the SDM generated, since the area where Salvia species grow in Chile is a coastal strip about 5 km wide, which is near the pixel size of 2.5 arc min used for the layers. Along with the imprecision of the information layers, this prejudices the classification for this coastal desert area. This same limitation is reflected in the fact that the transverse valleys in northern Chile are not expressed in the results. The Huasco and Copiapó valleys in the Atacama region may be very suitable for the cultivation of chia with irrigation. Thus the spatial resolution used in the models does not allow representation of the temperature conditions of the territory because they generalize the areas, losing the characteristics of the topoclimates or microclimates present in the territory. These are climates which deviate from the rest of the zone due to the influence of relief on the overall climate (Schnelle, 1968). There is also the possibility that the error in the thermal field of these areas is not due to the resolution of the grid, but to the quantity, locations of and distances between the climatological stations that were used to produce the bioclimatic layers of WorldClim (Hijmans *et al.*, 2005). Specifically, not including stations within the topoclimates may not allow adequate representation of this area in the thermal field. Given the information on the Salvia present in Chile, we infer that chia could probably live in sectors near these oases and in the coastal edge of Antofagasta region, but as a crop it would require irrigation. The coastal zones are exposed to salinity, and although chia may be cultivated with saline irrigation water of 3.0 dS/m, oil production decreased by 20% (Heuer *et al.*, 2002).

Baginsky *et al.* (2016) reported the grain and biomass yields of chia in three experimental crops: Azapa (Arica), Canchones (Iquique) and Las Cruces (Fig. 5B). These results were used to compare with our climatic zoning, to approximate an *in situ* validation. The 2013 grain yields were economically sustainable in Azapa (18°20' S; 70°01' W) and Canchones (20°26' S; 69°32' W) stations, which are at around 18° and 20° S latitude, but Azapa has climatic influence from the coast. The Las Cruces station (33°30' S; 71°36' W) had low grain yield due to frosts that affected the development of the crop. All three stations produced economically sustainable biomass both in the central and northern zones of the country (Baginsky *et al.*, 2016). In spite of these good results, none of the stations was classified in the highest suitability categories; Canchones was in the "moderately suitable" category, while Azapa and Las Cruces were "marginally suitable". In contrast to its classification, Baginsky *et al.* (2016) considered that Azapa was the station with greatest and most stable yields. This incongruence has the same explication as the classification of the oases with Salvia discussed above, the lack of representation of the topoclimates present in the localities of the experimental stations, given the spatial resolution and the quality of the raster layers used in the models. We may infer that biomass production zones have a wider temperature range than seed production zones, that is, biomass production is possible in the temperature tolerance range of the species, while seed production should be in the optimal range, which is confirmed by the low seed yields of the Las Cruces station. Thus areas in the "moderately suitable" and "marginally suitable" categories are adequate for biomass production, since the zoning was conditioned to determine the optimal places to plant chia for seed production.

Chia is a short day plant, with a 12 hour photoperiod threshold for flower induction (Ayerza & Coates, 2006). Given the wide range of latitudes of Chile, the varying photoperiod is a factor that must be considered in the zoning. Hildebrand *et al.* (2013) suggested that seed production is restricted to 22°55' north latitude and 25°05' south, since at latitudes 32°14' north and 39°11' south the species dies before flowering due to frosts. Dogliotti (2011) suggested that high temperatures and long photoperiods accelerate plant growth and decrease seed yield, thus this is an important factor to consider. These suggestions concur with the result of the world SDM of chia of this study, since they considered latitudes near the tropics; however, there is chia cultivation in latitudes greater than the tropics established in greenhouses in controlled conditions (Jamboonsri *et al.*, 2012). These authors proposed a variety of chia seed that allows lengthening the photoperiod, allowing flowering to be induced earlier and thus seed production before the period of frosts; this was evaluated in some localities of the USA. Access to these varieties might allow chia to be planted in other zones such as the central regions of Chile with good seed yields. Salinity does not appear to affect chia importantly, since it produced good results in the stations near the coast, thus the coastal edge has good potential for the establishment of crops. We calculated that to satisfy the demand of 645 tons which Chile had in 2011 (De Kartzow, 2013) about 430 ha would be required, in accordance with a yield of 1500 kg/ha, which was the minimum yield for the stations of Azapa and Canchones station in 2013.

Finally, we conclude that rainfed chia cultivation is not feasible in Chile due to its tropical climate. Nevertheless, chia cultivation for grain or biomass production is possible with irrigation in the northern zone of Chile (regions of Arica y Parinacota, Tarapacá, Antofagasta and Atacama), since the temperature is adequate, while the central zone (regions of Coquimbo, Valparaíso, Metropolitana and Maule) is only suitable for biomass production. Although the most suitable zones are in both the intermediate depression and coastal edge of the regions mentioned above, we recommend giving priority to the coastal edge because of the lower thermal oscillation due to the homogenizing effect of the sea and the fog. Moreover crops between the city of Antofagasta and Taltal could possibility require less irrigation in foggy conditions. We also recommend generating a zoning for chia in Chile according to the possible scenarios of climate change, to give priority for zones that would maintain or improve good feasibility for the crop. The inclusion of chia in Chilean agriculture may be an option to widen the agricultural matrix and incorporate this functional food into the culture and idiosyncrasy. Despite it is not native to the country; it could be an exotic cultivated species that contributes to the health of the people.

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