ECOLOGY & BIOGEOGRAPHY - ORIGINAL ARTICLE

Global invasibility potential of the shrub *Baccharis drancunculifolia*

Ulises Olivares-Pinto[1] · Newton P. U. Barbosa[2,3] · Geraldo Wilson Fernandes[3]

Abstract

The genus *Baccharis* (Asteraceae) comprises over 440 species distributed along North and South America. Some species of this genus have remarkable invasiveness, and one of these species is the South American shrub *Baccharis dracunculifolia DC*. Most of the introductions of non-indigenous species are held indirectly through trade, so it is believed that this species could become invasive worldwide with a particular interest in the North American continent because of the increasing sale of products derived from honey to this continent. The resin extracted from *B. dracunculifolia* is the leading source for preparing the green propolis produced in Southeastern Brazil. Thus, the main objective of this work is to apply an approach based on distribution modeling to investigate possible areas of high environmental suitability for *B. dracunculifolia* in the North American continent and the potential to the entire globe using current and two future scenarios. Our results show many areas of environmental suitability for *B. dracunculifolia*. This species can invade over 33 countries distributed into five continents, including North America, some of the most critical parts of the southern USA, and large areas in Mexico. Since the best way of countering biological invasions is prevention, we propose that the introduction of this species should be monitored.

Keywords Biological invasion · Climate matching · Maximum entropy · Model selection · Niche · Projection scenarios

1 Introduction

The genus *Baccharis* L. (Asteraceae) (Linnaeus 1753) comprises more than 440 species and is distributed from Southern North America to Southern South America (Abad and Bermejo 2007; Fernandes et al. 2021; Heiden 2021). Some species of this genus have remarkable invasiveness potential traits, such as generalist behavior, effective dispersal mechanism, adaptation to pioneer stages of succession, high competitive ability, and seeds germinate under a wide range of environmental conditions (Fernandes et al. 2021;

Lázaro-Lobo et al. 2021). *Baccharis halimifolia* L. (Linnaeus 1753) and *Baccharis pilularis* DC. (Candolle 1836), both native to North America, and *Baccharis dracunculifolia* DC. (Candolle 1836), native to South America, are known for their invasive potential.

B. halimifolia L. is native to North America, and it is found at high density in disturbed sites in North American prairies (Allain and Grace 2001; Valéry et al. 2009). It is a successful invader of estuarine communities in Southern Europe (Caño et al. 2012; Fried et al. 2016; Calleja et al. 2019a, b). *Baccharis halimifolia* is sensitive to changes in environmental conditions such as light and temperature (15–20 °C) for optimum yield (Westman et al. 1975). Also, *B. halimifolia* is sensitive to soil conditions, e.g., water-logged conditions, high soil slit, and high conductivity, which seem to reduce its presence (Fried et al. 2016). Additionally, *B. halimifolia* has shown higher germination rates at low salinities and soils farther from the immersion influence of estuaries (Paudel et al. 2013). Some of the extreme effects when *B. halimifolia* is exposed to salinity are drastic biomass reduction, short plant height, and lower leaf production (Caño et al. 2013, 2016; Calleja et al. 2019a, b). Previous reports of *B. halimifolia* exposure to salinity showed intolerance at ranges > 30 g/l (Caño et al. 2014; Fried et al. 2016).

✉ Geraldo Wilson Fernandes
gw.fernandes@gmail.com

Ulises Olivares-Pinto
uolivares@unam.mx

1   Escuela Nacional de Estudios Superiores Unidad Juriquilla, Universidad Nacional Autónoma de México, Juriquilla, Querétaro 76230, México

2   Bioengineering Centre of Invasive Species – CBEIH, Belo Horizonte, MG, Brazil

3   Departamento de Genética, Ecologia & Evolução, Universidade Federal de Minas Gerais, CP 486, Belo Horizonte, MG CEP 30161-970, Brazil

Baccharis pilularis DC., also originated in North America, has been responsible for the shrub encroachment of prairie regions, driven primarily by the change in land use and other human impacts (Davis and Mooney 1985; Hobbs and Mooney 1986; Williams and Hobbs 1987). Moreover, *B. pilularis* can become more invasive due to its large seed production, long-distance dispersion, wide adaptability to soil nutrient conditions, and salinity compared to noninvasive species (Fernandes et al. 2021). Also, *B. pilularis* has proliferated in large regions in response to increased temperature and atmospheric CO_2 concentrations due to a drastic reduction of herbivory by snails and slugs (Gastropoda: Pulmonata), the most frequently observed herbivores on *B. pilularis* seedlings (Zavaleta 2005).

Baccharis dracunculifolia DC. is native to South America and considered a weed in disturbed, degraded areas (Lorenzi 1991; Gomes et al. 2002) and has a quick life cycle that increases its distribution properties (Fagundes et al. 2001, 2005; Gomes 2002; Espírito-Santo et al. 2003). This species is distributed throughout the Brazilian Cerrado (Gomes 2002), sea coast (Fagundes and Fernandes 2011), tropical rainforest (Fagundes and Fernandes 2011), and pampas of Brazil, Uruguay, Paraguay, Argentina (e.g., Altesor et al. 2005; Minteguiaga et al. 2021), Peru (Grant 2020), and Bolivia (Loayza et al. 1995); for reviews, see Fernandes et al. (2021).

Although there are no reports of *B. dracunculifolia* introduction in North America, the growing trade of honey-derived products between Brazil and the USA (Oliveira et al. 2021), which encompassed almost 27,360 tons of natural honey alone in 2020, can facilitate the invasive potential of *B. dracunculifolia* into North America (Abemel 2015). It is known that the resin extracted from *B. dracunculifolia* is the primary source for the preparation of green propolis, a resinous derived product produced in Southeastern Brazil (Alencar et al. 2005; Fernandes et al. 2018). Much of the introductions of non-indigenous species are held unintended by transporting seeds/seedlings by humans, from one region to another through trade and tourism (e.g., Lockwood et al. 2005; Reichard et al. 2009); these introductions occur mainly in urban areas (Von der Lippe et al. 2008). The achenes of *B. dracunculifolia* are tiny (between 1 and 2 mm) and resistant, facilitating their transport by crates or other materials originating from honey-producing regions in Brazil to the USA (Oliveira et al. 2021). Furthermore, given its high value in the North American market, there is a high chance for this species to be introduced into North America to be used for the production of green propolis (Amancio et al. 2021; Oliveira et al. 2021). *B. dracunculifolia* is a species whose distribution is growing in South America, mainly due to climate change and increasing human impacts (Gomes and Fernandes 2002). Thus, a potential invader if introduced into

North America, mainly because it can adapt to different habitats (highlands, wet or dry, hot, or cold, see Fagundes and Fernandes 2011), makes this species an attractive model to study biological invasion.

The ability to predict the entry of an invasive species into a new environment is a much-discussed "biological invasion" topic in conservation biology (Nyari et al. 2006; Giovanelli et al. 2008b; Jiménez-Valverde et al. 2011; Elith 2017). Biological invasions had been a significant cause of loss of biodiversity on the planet, synergistically acting with other components of global change like climate change, habitat destruction, and pollution (Dukes and Mooney 1999; Ludsin and Wolfe 2001; Bacher et al. 2018; Malacrinò et al. 2020; Pyšek et al. 2020; Faria et al. 2022). Moreover, it has caused considerable losses to the global economic system, currently being configured as one of the biggest problems of global agribusiness (Crystal-Ornelas et al., 2021; Zenni et al. 2021). Fantle-Lepczyk et al. (2022) estimated expenditures of about $47 billion annually in the USA alone to control non-indigenous invasive species. These losses may reach 105 billion dollars a year for Brazil, including agriculture and human health (Adelino et al. 2021). Due to all these factors, in 1999, President Bill Clinton signed an executive order to create rules to prevent the entry of non-indigenous invasive species into the USA and also implemented guidelines for the management of these species to reduce the damages caused by them (Peterson and Vieglais 2001).

Species distribution models (SDM) have been used to predict areas of high invasibility for non-indigenous species into a new environment (Nyari et al. 2006; Giovanelli et al. 2008b; Pacifici et al. 2015; Bazzichetto et al. 2018). SDM is based on climatic matching between areas of origin and regions supposedly invaded; it is also recognized as an important tool for building environmental policies to control invasive non-indigenous species spread (Rodda et al. 2011). The SDM is developed by combining environmental data and species distribution, generating information on their potential distribution in areas (e.g., maps) with reasonable environmental suitability for this species (Zimmermann et al. 2010; Duarte et al. 2018). The SDM has been widely used in ecology to predict the effects of global warming on species and select priority areas for conservation (e.g., Elith et al. 2006; Peterson 2006; Barbosa et al. 2010; Pacifici et al. 2015; Zhang et al. 2021). In addition, it has been often used to describe potential areas of distribution where rare species could occupy (e.g., Raxworthy 2003; Giovanelli et al. 2008a; Barbosa et al. 2015). Furthermore, this approach has also been used to predict the potential entry areas/invasion routes of non-indigenous species (e.g., Vieglais and Peterson 2001; Papes and Peterson 2003; Peterson et al. 2003; Ficetola et al. 2007; Thapa et al. 2018).

The synergy provided by the broad spatial distribution, biological characteristics, and extensive use by humans of
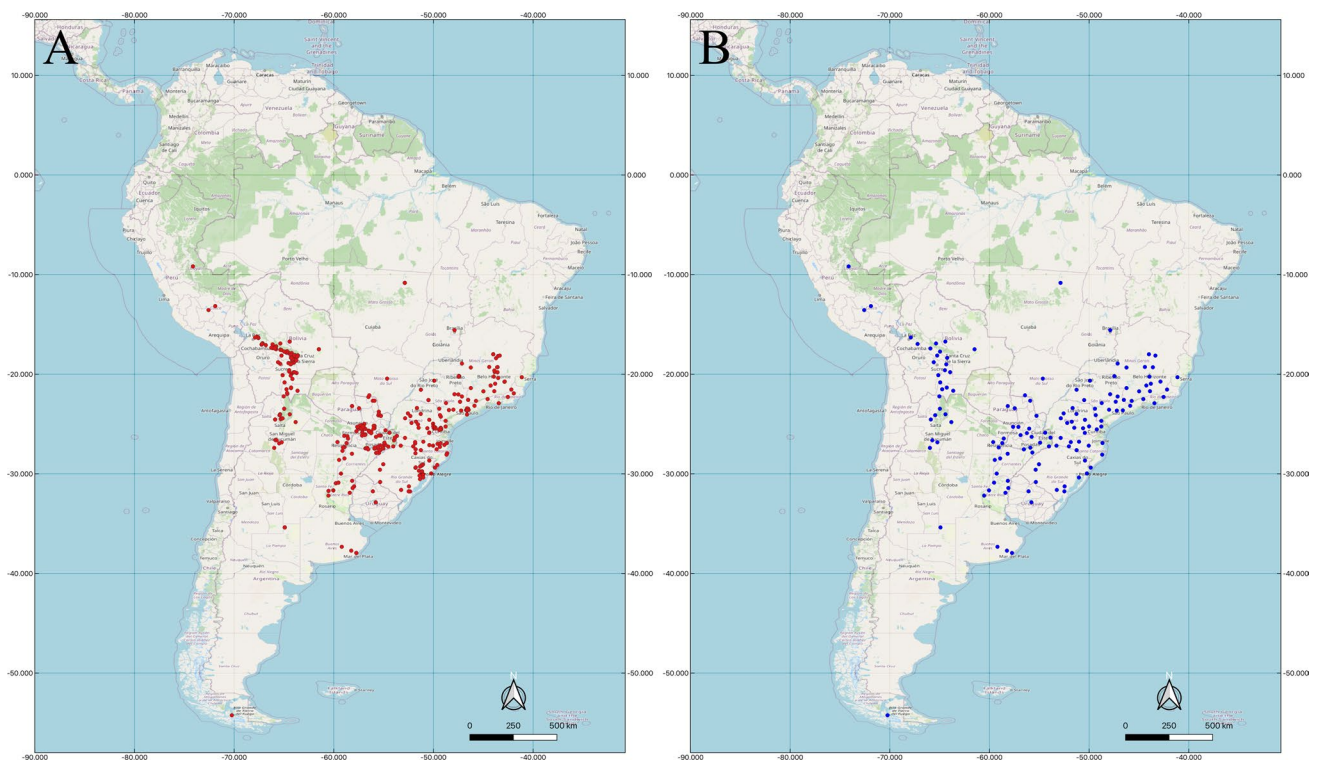
Fig. 1 Distribution of South American occurrences for *Baccharis dracunculifolia.* used in this study to develop the distribution model within the calibration area. (**A**) Original occurrences distribution from GBIF. (**B**) Curated occurrences distribution

the products supplied by *B. dracunculifolia* in line with the globalization and climate change scenarios provided the impetus for this study. This project sought an approach based on SDM to investigate possible entry areas with high environmental suitability for *B. dracunculifolia* on the North American continent and projection scenarios to find suitable conditions in which *B. dracunculifolia* can establish worldwide (Levine et al. 2003). Some possible impacts from the introduction of *B. dracunculifolia* worldwide could be: (i) change in the native plant community structure (Vivrette and Muller 1977; Pysek and Pysek 1995), (ii) impacts on higher trophic levels (Carrol et al. 1998; Schmidt and Whelan 1999), and (iii) impacts on hydrology and fire regimes (Van Wilgen and Richardson 1985; Gerlach 2000).

2 Materials and methods

Species and environmental data – We built the SDM using 1862 georeferenced occurrences of *B. dracunculifolia*, following the checklist provided in Feng et al. (2019) to ensure the reproducibility of methods. These occurrences were downloaded from the GBIF platform, all located in South America (GBIF 2021) (Fig. 1A). However, 1,304 occurrences were discarded because they overlapped in the same pixel, thereby reducing autocorrelation effects (Hernandez

et al. 2006; Phillips et al. 2006; Pearson et al. 2007; Thorn et al. 2009). The overlapped points were discarded using the *duplicated* function of the base R package (R Core Team 2021); remaining 558 occurrences and effects of spatial autocorrelation were avoided by thinning observations with a distance of 50 km using the *poThin* function of the RSpatial library (OShea 2021). From those 1862, a total of 209 occurrences were used for this study (Fig. 1B; Table S1), which were partitioned into two subsets being 75% for model calibration and 25% for testing; the random method of the ENMeval package was used to partition data (Muscarella et al. 2014).

Bioclimatic variables are good predictors for the distribution of biodiversity due to their strong associations with climate and biota (Mooney et al. 1995; Pearson and Dawson 2003; Schrag et al. 2008). Thus, the bioclimatic variables were obtained from the project Worldclim (2021) using a spatial resolution of $30''$ ($\sim 1 km^2$) (Fick and Hijmans 2017). However, the BIO8, BIO9, BIO18, BIO19 bioclimatic variables that combine temperature and precipitation were discarded for knowing odd discontinuities between neighboring pixels (see Escobar et al. 2014) (Table 1). The altitude variable has demonstrated to be also a good predictor for the distribution of biodiversity (Parolo et al. 2008), it was used in conjunction with all other groups of variables, and it was also

Table 1 List of environmental variables (included and excluded) used in this study for the distribution model for *Baccharis dracunculifolia*

Included Variables	Excluded Variables	Spatial resolution	Reference
Altitude		30″ (~ 1 km)	*WorldClim*
Aspect		30″ (~ 1 km)	(Fick and Hijmans 2017)
Slope		30″ (~ 1 km)	
BIO 1 = Annual Mean Temperature*		30″ (~ 1 km)	
BIO 2 = Mean Diurnal Range		30″ (~ 1 km)	
BIO 3 = Isothermality		30″ (~ 1 km)	
BIO 4 = Temperature Seasonality*		30″ (~ 1 km)	
BIO 5 = Max Temperature of Warmest Month		30″ (~ 1 km)	
BIO 6 = Min Temperature of Coldest Month*		30″ (~ 1 km)	
BIO 7 = Temperature Annual Range*		30″ (~ 1 km)	
	BIO 8 = Mean Temperature of Wettest Quarter	30″ (~ 1 km)	
	BIO 9 = Mean Temperature of Driest Quarter	30″ (~ 1 km)	
BIO 10 = Mean Temperature of Warmest Quarter*		30″ (~ 1 km)	
BIO 11 = Mean Temperature of Coldest Quarter*		30″ (~ 1 km)	
BIO 12 = Annual Precipitation*		30″ (~ 1 km)	
BIO 13 = Precipitation of Wettest Month		30″ (~ 1 km)	
BIO 14 = Precipitation of Driest Month		30″ (~ 1 km)	
BIO 15 = Precipitation Seasonality (Coefficient of Variation)		30″ (~ 1 km)	
BIO 16 = Precipitation of Wettest Quarter*		30″ (~ 1 km)	
BIO 17 = Precipitation of Driest Quarter*		30″ (~ 1 km)	
	BIO 18 = Precipitation of Warmest Quarter	30″ (~ 1 km)	
	BIO 19 = Precipitation of Coldest Quarter	30″ (~ 1 km)	

*Variables used in the model

obtained from the Worldclim project at a spatial resolution of 30″ (~ 1km^2) (Fick and Hijmans 2017) (Table 1). The variables derived from the altitude, aspect, and slope were created using the *terrain* function of the *raster* R package (Hijmans 2021).

All bioclimatic variables were cropped to cover the calibration area (M) in South America, covering all occurrences of the species (Fig. 1B). For this purpose, the *convex_area* function with a buffer_distance of 75 km was used and was performed in the *ellipsenm* v0.3.4 R package. Also, a Pearson correlation test was performed to avoid the presence of multicollinearity between variables (Zar 1996). Those highly correlated ($r \geq 0.8$) were kept in the model as qualitative variables (Werneck et al. 2010). Furthermore, a jackknife process in Maxent (Phillips et al. 2018) was used to select distinct sets of variables that most contributed to models (Table 1). The *findCorrelation* function of the *caret* R package (Kuhn et al. 2020) was applied to select resulting bioclimatic variables. Further, a principal component analysis (PCA) was carried out to visualize the niche of *B. dracunculifolia* using the Niche Analyst tool (Qiao et al. 2016).

The resulting nine bioclimatic variables were grouped into 10 sets of eight/nine variables (Tables 2 and 3) using the

Table 2 Performance statistics for the four best SDM models based on independent 10 occurrence data of *Baccharis dracunculifolia*

Model Number	Set of variables	Mean AUC ratio	Partial ROC	Omission rate
1	Set 10	1.5073	0	0.111
				0
2	Set 2	1.5689	0	
3	Set 4	1.5782	0	0
4	Set 6	1.5872	0	0

kuenm_varcomb function of *kuenm* R package (Cobos et al. 2019). In addition, two projection scenarios (2030 and 2050) and two representative concentration pathways (RCP) (RCP 4.5 and RCP 8.5) were evaluated, and the NCAR-CCSM4 general circulation model (GCM) for 2030 and 2050 time projections. Data were downloaded from the CGIAR spatial downscaling database (Navarro-Racines et al. 2020; CGIAR 2021).

Model calibration – For the SDM calibration process, 5,270 models were evaluated by combining ten sets of

Table 3 Sets of bioclimatic variables used to evaluate the SDM models

Set of bioclimatic Variables	Variables
Set 2	BIO1, BIO4, BIO7, BIO10, BIO11, BIO12, BIO16, BIO17
Set 4	BIO1, BIO4, BIO6, BIO7, BIO10, BIO11, BIO12, BIO16
Set 6	BIO1, BIO4, BIO6, BIO7, BIO10, BIO11, BIO16, BIO17
Set 10	BIO1, BIO4, BIO6, BIO7, BIO10, BIO11, BIO12, BIO16, BIO17

environmental predictors, considering the contribution of each predictor's regularized training gain. In addition, 17 values of regularization multiplier were used: [0.1, 1] using intervals of 0.1, [1.0, 6.0] using intervals of 1.0, and [8.0, 10] with intervals of 2.0. Also, 29 combinations of all feature classes were used: linear, quadratic, product, threshold, and hinge. Candidate model performance was evaluated using the statistical significance metric partial ROC (pROC), with 500 iterations, 50% of bootstrapping, and omission rates of 5%. Finally, omission rate (OR) and Akaike information criterion corrected (AICc) were used as model selection criteria. With this combination of parameters, the best models were selected according to the following criteria: (1) significant models, (2) OR (≤ 0.5), and (3) AICc values (≤ 2) (Table 2) (Cobos et al. 2019). The creation and selection of models were performed using the *kuenm_cal* and *kuenm_ceval* functions of the *kuenm* R package.

The construction of each SDM was executed by an algorithm that uses the maximum entropy approach, which has shown the best performance among several other modeling methods (Elith et al. 2006; Hernandez et al. 2006), and can perform practical analysis even with small samples (Hernandez et al. 2006; Pearson et al. 2007; Thorn et al. 2009) using only present data (Phillips et al. 2006). The SDM was performed in MaxEnt software 3.4.4v (Phillips et al. 2006; Steven et al. 2021).

Model evaluation and extrapolation risk – The final SDM models were selected based on the best combination of parameters, with 500 replicates as bootstrap and logistic outputs. Then, they were evaluated with calculations of partial ROC and omission rates of 5% using 58 independent occurrence data points of *B. dracunculifolia* (Table 4) and performed with the *kuenm_mod* and *kuenm_feval* functions of the *knuem* R package (Cobos et al. 2019). These resulting SDM models were later projected to the entire world to find potential climate matching in areas where *B. dracunculifolia* could potentially establish, with a particular interest in North America.

Also, two pathways were evaluated using the NCAR-CCSM4 general circulation model (GCM). Extrapolation risk was calculated using the mobility-oriented parity (MOP) analysis (Owens et al. 2013) included in the *kuenm_mmop* function of the *kuenm* R package. This function compares the environmental variables between the calibration area

and the extrapolated areas. As a result, areas where strict extrapolation risk exists and similarity levels between the projection regions and the calibration area are obtained. Also, descriptive statistics were calculated to get the amount of variation across multiple parameter settings and see variance among models transferred to the projection areas, using the *kuenm_modstats* function of the *kuenm* R package.

Lastly, to ensure reproducibility of methods, the authors created a GitHub repository in which source code and data are available for the following tasks: (1) cleaning and preparing occurrence data, (2) selecting bioclimatic variables, and (3) calibrating models, select best models, extrapolation, and risk evaluation. This repository can be found in the Data and Source Code Availability section.

3 Results

After applying a correlation analysis, only nine highly correlated variables ($r \geq 0.8$) were kept in the model (Fig. 2, Table 1). According to the jackknife results, the bioclimatic variables that most contributed to the training gain of the final SDM models were: annual mean temperature (BIO 1), temperature seasonality (BIO 4), min temperature of coldest month (BIO 6), temperature annual range (BIO 7), mean temperature of warmest quarter (BIO 10), mean temperature of coldest quarter (BIO 11), annual precipitation (BIO 12), precipitation of wettest quarter (BIO 16), and precipitation of driest quarter (BIO 17) (Fig. 3). The importance of these variables for *B. dracunculifolia* had been previously reported (Gomes and Fernandes 2002; Fagundes and Fernandes 211). The SDM evaluation using variables cited above resulted in four selected models (Fig. 4). Three-dimensional environmental space convex hull denotes the environmental distribution of *B. dracunculifolia* in South America (Fig. 5).

The SDM models resulted in two types of maps, being the first a habitat suitability (invasibility) map projection with higher environmental suitability denoting a potential distribution for *B. dracunculifolia* (Fig. 6), which depicts the invasive potential of *B. dracunculifolia* for the current scenario (Hirzel and Le Lay 2008; Estay et al. 2014; Avendaño et al. 2021). Also, two future projections were evaluated for 2030 and 2050 using the CCSM4 GCM and the pathways RCP 4.5 intermediate scenario emissions

Table 4 Performance statistics for the best four SDM candidate models during calibration for *Baccharis dracunculifolia*

SDM Model Number	Mean AUC ratio	Partial ROC (pROC)	Omission rate (OR) at 5%	OR_AICc	Delta AICc	W AICc	Number of parameters
1	1.381	0	0.034 0.034	6128.689	0.000	1.000	15
2	1.389	0		6128.689	0.000 0.001	0.250	15
3	1.384	0	0.034	6128.689	0.0001	0.334	15
4	1.388	0	0.034	6128.696	0.0007	0.499	15
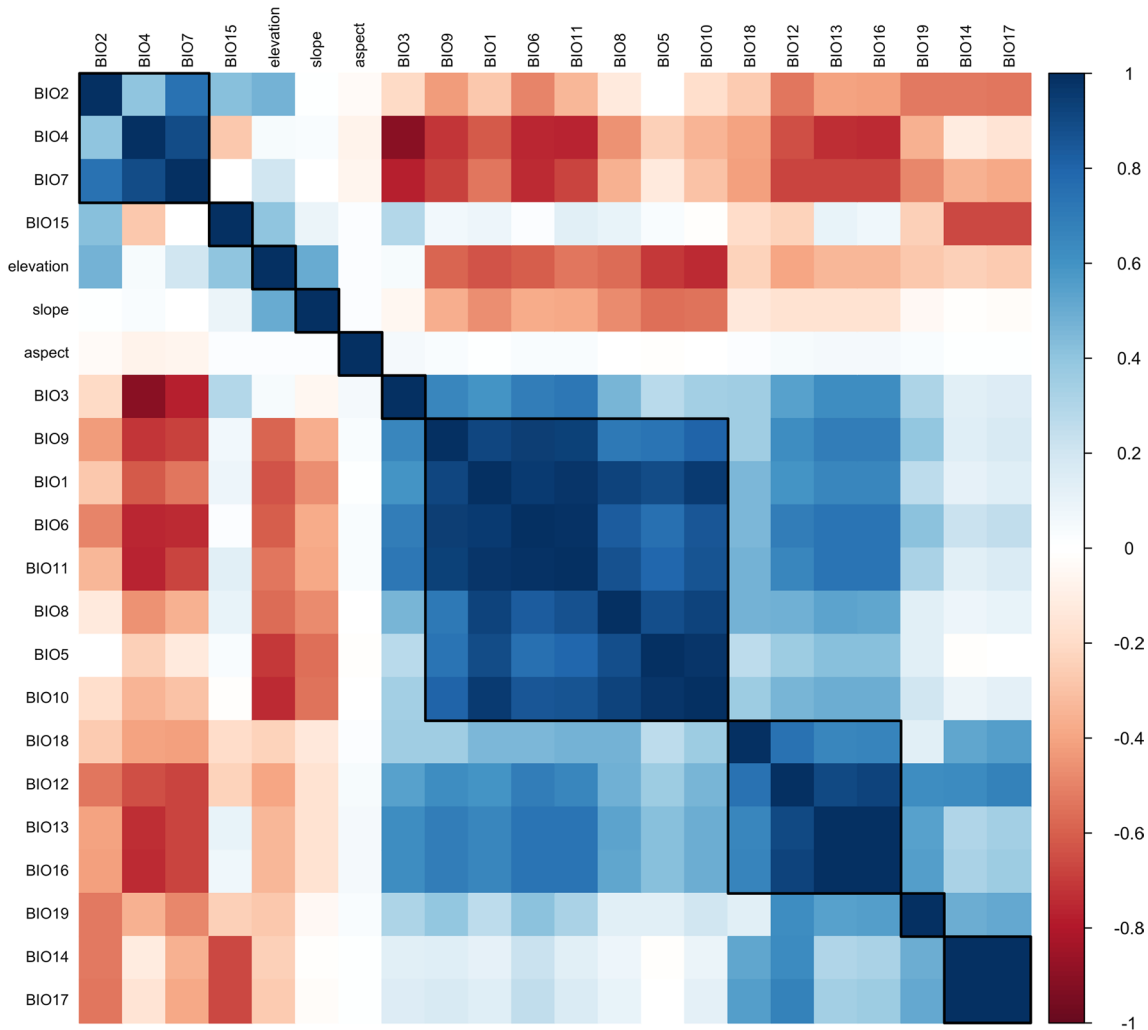
Fig. 2 Correlation matrix of environmental variables of calibration area in South America. Legend depicts the correlation between variables, ranging from −1 to 1. Squares denote highly positively correlated variables

peak around 2040 then declined, and RCP 8.5 emissions continue to rise throughout the twenty-first century. These two pathways represent variations in climatic conditions and allow us to simulate the response of *B. dracunculifolia* under these climatic conditions.

The invasiveness potential of *B. dracunculifolia* increases over time and is slightly positively accentuated with the increase in greenhouse gas emissions in RCP 8.5 (Fig. 7). Each map in Fig. 7 represents the average values of four sets of environmental variables using logistic outputs for the final selected models. Additionally, logistic outputs were binarized into two classes that denote suitability or unsuitability for *B. dracunculifolia* for a given area (Saunders et al. 2020). The second type map denotes
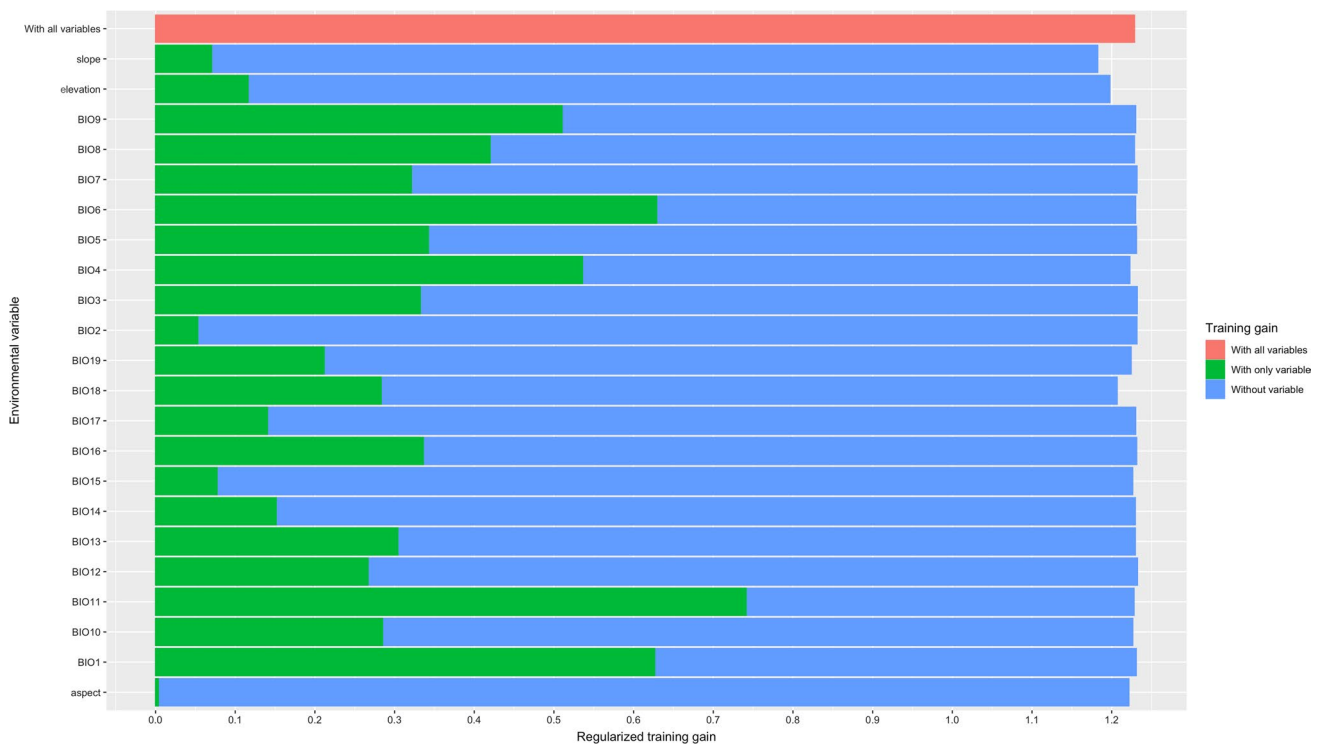
Fig. 3 Model contribution of environmental variables evaluated using the jackknife process. Legend denotes training gain using all variables (red bar), individual variables (green bars), and training gain using all variables except the indicated one (blue bars)

the extrapolation risk map projection, in which higher environmental similarity indicate broad areas of strict extrapolation for *B. dracunculifolia* (Owens et al. 2013; Cobos et al. 2019; Obiakara et al. 2020; Raghavan et al. 2020) (Fig. 8).

Accordingly, potential impacts of the introduction of *B. dracunculifolia* were evaluated using model transfer for two future scenarios (see Figs. 7 and 8). The CCSM4 GCM was used, and two representative concentration pathways are as follows: RCP 4.5 and RCP 8.5. The SDM results suggest that variables related to temperature per se, in general, have greater importance than those related to precipitation. The distribution areas of native *B. dracunculifolia* in Southeastern South America have high precipitation levels during the summer.

Furthermore, there is a high risk of invasion into the African continent in South Africa, Zimbabwe, Namibia, Angola, Zambia, Mozambique, Tanzania, Kenya, Etiopia, Angola, Madagascar, Morocco, and some parts of the Congo Republic. Also, in Europe, there is a high risk of invasion in Portugal, Spain, France, Ireland, the UK, and some regions of Italy, Libano, and Israel. Similarly, other *Baccharis* spp. are also established in Europe and classified as invasive, indicating a high probability of proliferation for *B. dracunculifolia* if introduced (Fried et al. 2016). Additionally, there is a high risk of invasion in Asia in China, Taiwan, Vietnam, Laos, Camboya, Thailand, Burma, Bangladesh, India, and Nepal. This high risk is also persistent in Australia, Tasmania, New Zealand, and New Caledonia.
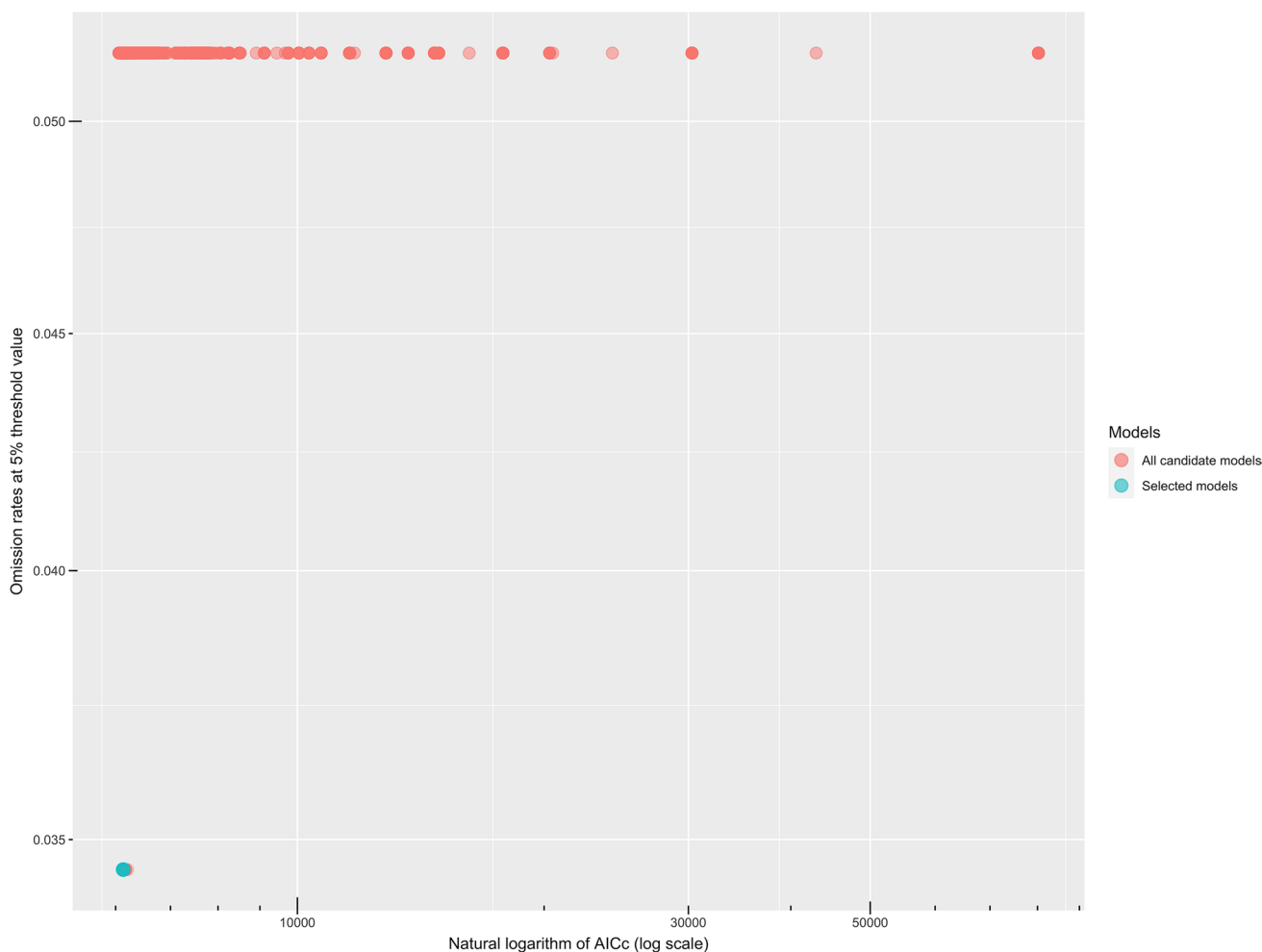
Fig. 4 Selected models that met the omission rate (OR) or Akaike information criterion corrected (AICc) criteria. The four selected models overlapped on the same point

4 Discussion

The area of introduction of an invasive non-indigenous species often reflects a more significant extension of suitability than that found in the native field (Fitzpatrick et al. 2007; Kearney et al. 2008). Nonetheless, our projection results of *B. dracunculifolia* suggest that this affirmation has to be reconsidered for this species. In all the cases except Africa, the highest suitability is located in South America, South China, and Eastern Australia. Darwin (1859) postulated that most species seem to have a limited distribution in nature, and these limitations are more a result of biotic rather than

by climatic factors. However, the model presented here encompasses probably a significant portion of the fundamental niche for *B. dracunculifolia*, given the wide range of habitats colonized by this species in South America (Gomes and Fernandes 2002; Marques et al. 2002; Altesor et al. 2005; Loayza et al. 1995; Fagundes and Fernandes 2011). Thus, the future projections probably reflect much of the species' fundamental niche worldwide. Likewise, the climatic similarity of areas where a species can proliferate is only one aspect to consider. In addition, other aspects to consider are nutrient availability, light availability, and salinity (Lázaro-Lobo et al. 2021).
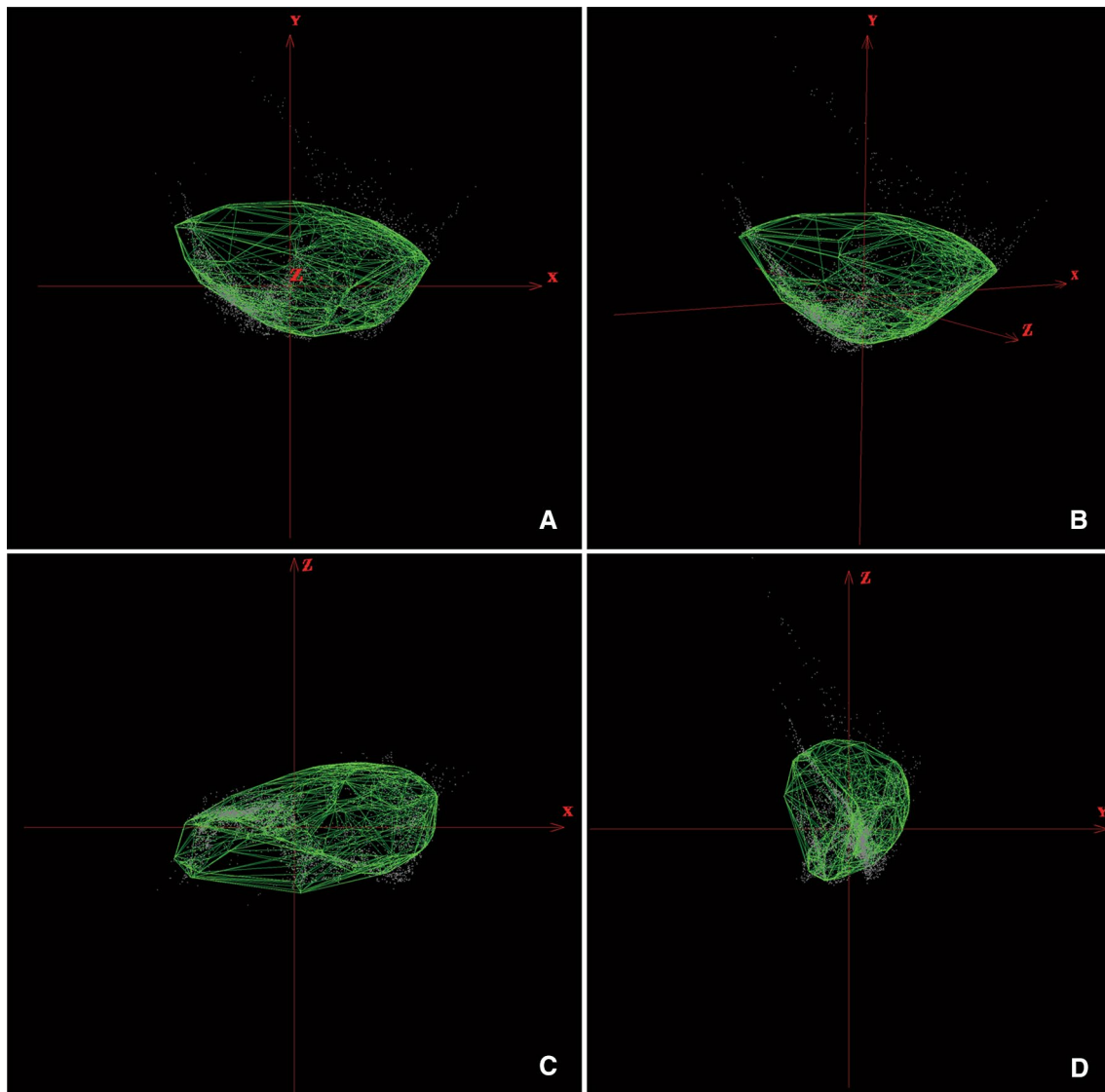
Fig. 5 Distribution of *Baccharis dracunculifolia* using a representation of three-dimensional environmental space using PC1 (proportion of variance 0.7392, X-axis), PC2 (proportion of variance 0.1677, Y-axis), and PC3 (proportion of variance 0.0691, Z-axis). (**A**) View of the niche based on PC1 and 2, (**B**) view of the niche based on PC 1, PC2, and PC3, (**C**) view of the niche based on PC 1 and 3, and (**D**) view of the niche based on PC2 and 3

Realized climatic space for *B. dracunculifolia* is denoted by a convex hull. The background cloud of points denotes all the possible climates in the calibration area (Qiao et al. 2016). Besides, the convex hull represents the environmental conditions in which *B. dracunculifolia DC.* can proliferate in a certain period (Qiao et al. 2017). However, the climate is dynamic, and currently, it is constantly changing due to the anthropogenic activities that produce greenhouse gas emissions (Kaufmann et al. 2011; Zwiener et al. 2018). Formerly, new scenarios must be evaluated assuming different emission pathways to assess whether this species can proliferate under different climate conditions in future periods and other geographic regions (Gong et al. 2020). Additionally, other aspects related to biotic, abiotic, and accessibility conditions of a species to a given area should be considered. This last aspect is of great relevance in species
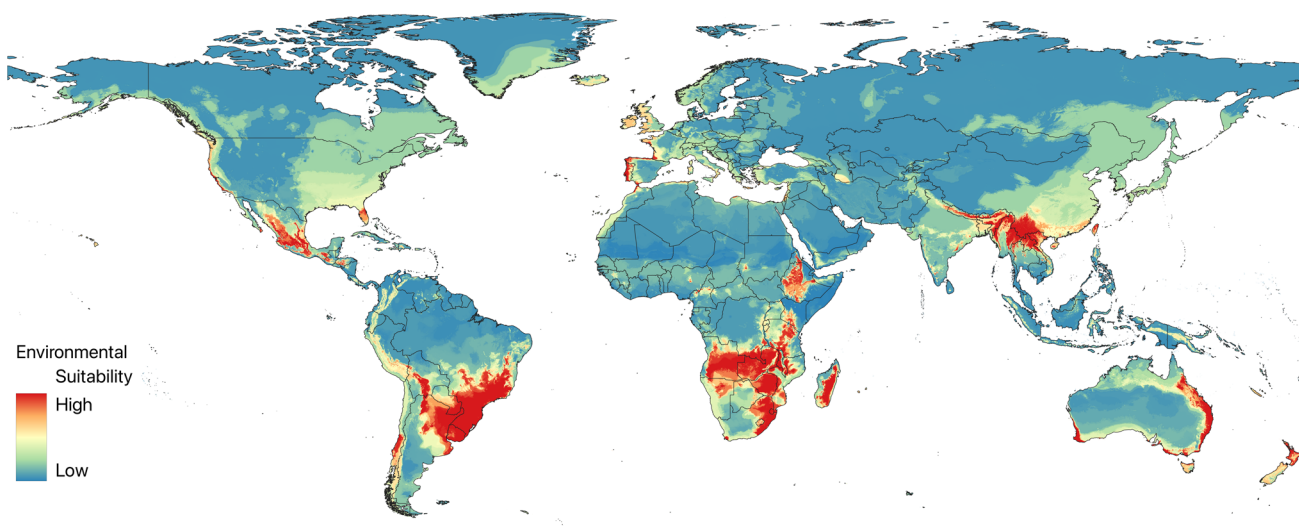
Fig. 6 Environmental suitability map in current pathway with a logistic projection of the final 4 SDM models meeting the selection criteria OR and AICc to the entire world, allowing extrapolation and clamping. Legend denotes environmental suitability, higher environmental suitability denoting a potential distribution for *B. dracunculifolia*

whose exploitation represents an economic benefit or trading products. This interest facilitates the introduction of species in areas in which species are not naturally distributed. That is the case with the increased demand for honey-derived products obtained from *B. dracunculifolia* (Lázaro-Lobo et al. 2021).

The environmental suitability of the current scenario for *B. dracunculifolia* in North America encompasses some of the most critical ports of the west coast of the USA, in states such as California, Oregon, and Washington. Thus, the results based on climate matching between the natural habitat of *B. dracunculifolia* and North America show us that much of the west coast and Florida have a high risk of invasion by this species. In addition, a half territory of the USA is a mid-risk of invasion, at least 29 states. Part of the central region of the USA, in areas of significant incidence of livestock activities, agriculture, and grasslands, also presents favorable conditions for establishing this species if it is introduced. Furthermore, there are large areas of high environmental suitability for *B. dracunculifolia* in Mexico. At least 20 states are at high risk. Also, there are broad areas at high risk in Guatemala, Dominican Republic, and Honduras. Mid-risk of invasion is also present in Cuba, Haiti, Jamaica,

and Puerto Rico. The fact that other species of *Baccharis* are present in these areas and are recognized as pests of agriculture indicates that *B. dracunculifolia* can become invasive in these regions since the realized niche tends to be retained over time (Peterson et al. 1999).

The rest of the North American continent presents a cold and drier climate that is unsuitable for establishing *B. Dracunculifolia*. Several studies have correlated climate correspondence to success in establishing some non-indigenous invasive species, indicating the importance of this approach in preventing and identifying invasions (e.g., Blackburn and Duncan 2001; Duncan et al. 2001; Forsyth et al. 2004). In addition, several plant species failed to settle in certain regions predicted as unsuitable for them (Grace 1987; Kornas 1990; Williamson and Fitter 1996; Pyšek 2003).

The transfer for future scenarios is a common practice in current studies that evaluate the invasiveness potential of species (Sequeira et al. 2018). Nonetheless, these transfers can lead to incorrect extrapolations (Elith et al. 2011). The mobility oriented parity (MOP) metric was conceived to lead with incorrect extrapolations by improving identifications of extrapolative areas (Owens et al. 2013). According to the extrapolation risk map, *B. dracunculifolia* could invade over
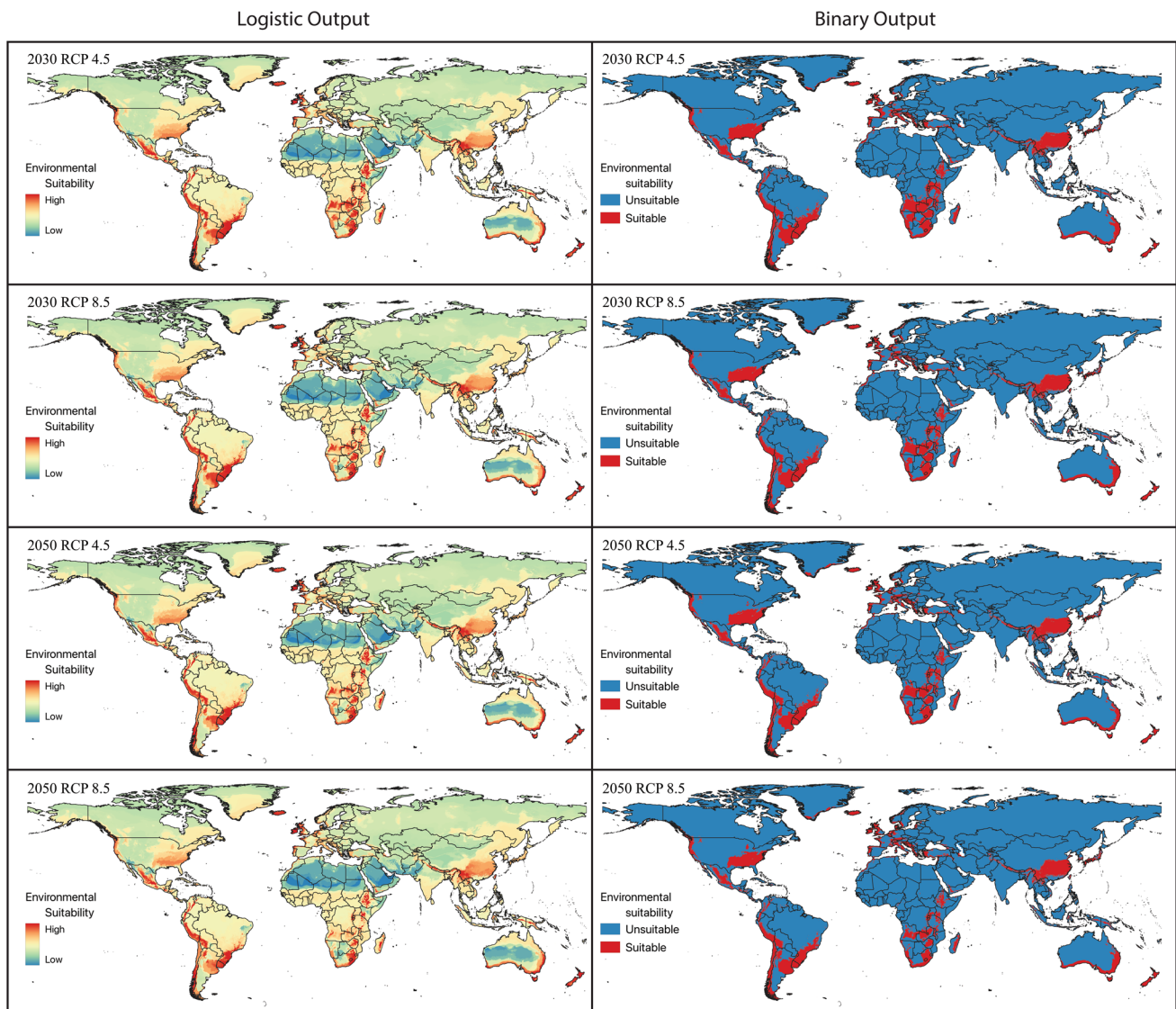
Logistic Output   Binary Output

Fig. 7 Environmetal suitability map in future projections based on logistic and binarized outputs of the final 4 SDM models meeting the selection criteria OR_AICc through the entire world using the ccsm4 GCM and RCP 4.5 and RCP 8.5 pathways, allowing extrapolation and clamping

33 countries across North America, Africa, Europe, Asia, and Australia. The environmental similarity is present in broad areas around the world. The North American region is of particular interest due to an increased trade of honey-derived products between South America and the USA.

Otherwise, with increasing trade with China, a great potential exists for that country, particularly in its southern region. Figure 8 evaluates more robustly the extrapolation risk for *B. dracunculifolia* in future scenarios worldwide. As a result, a high invasiveness potential is present in the same regions

Fig. 8 Extrapolation risk map in future projections (MOP results) using the ccsm4 GCM and 4.5 and 8.5 pathways. Legend indicates environmental similarity where higher values indicate broad areas of strict extrapolation for *B. dracunculifolia*
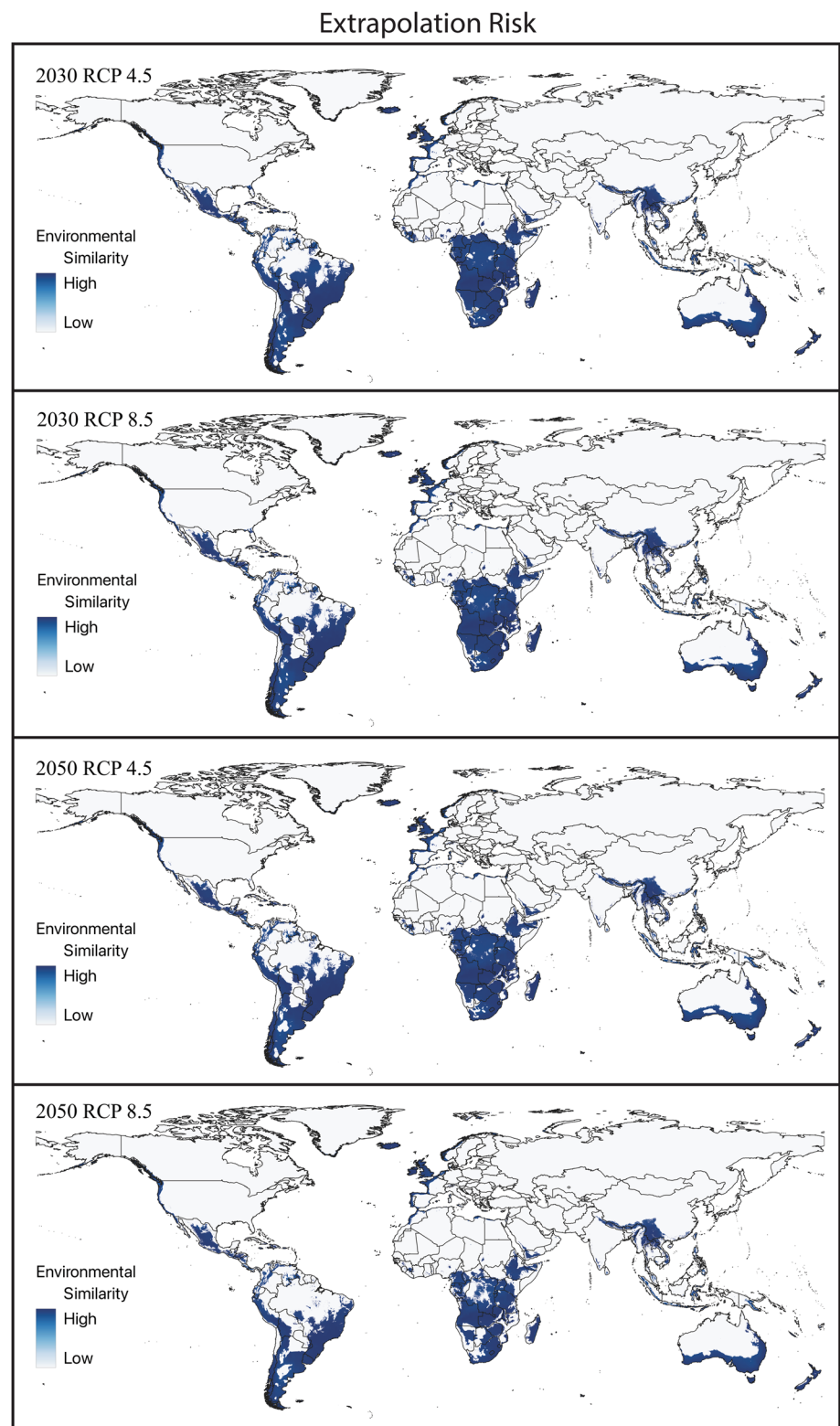
displayed in Fig. 7. However, there is an evident increase of risk in the African continent and a slight risk decrease in North America (the USA) and the Asian continent. This extrapolation confirms that this species can proliferate over time. Nonetheless, it also shows a loss of environmental conditions in RCP 8.5, especially in the African continent, which suggests that an increase of greenhouse gas emissions negatively affects ideal conditions that allow *B. dracunculifolia* to proliferate.

The best way to combat an invasive species is prevention (Richardson and Thuiller 2007). Once established, eradicating an invasive species is extremely difficult or impossible (Koch et al. 2006). Thus, there must be efforts to predict the entry of an invading species in a given territory (Committee on the Scientific Basis for Predicting the Invasive Potential of Non-indigenous Plants and Plant Pests in the United States 2002). We propose that given the risk of invasion by *B. dracunculifolia* discussed earlier, projects of introduction of this species should be monitored.

Declarations

Conflict of interest The authors declare no competing interests.

Data and source code availability Occurrence data and source code for (1) cleaning and preparing occurrence data, (2) selecting and crop bioclimatic variables, and (3) calibrating models, extrapolation, and risk assessment are available in the following GitHub repository https://github.com/HpcDataLab/B.drancunculifolia_Invasion.

References

Abad MJ, Bermejo P (2007) *Baccharis* (Compositae): a review update. ARKIVOC 2:76–96

Abemel (Brazilian Association of Honey Exporters) (2015) Dados da Exportação de Mel. https://brazilletsbee.com.br/. Accessed 01 Mar 2022

Adelino JRP, Heringer G, Diagne C, Courchamp F, Faria LDB, Zenni RD (2021) The economic costs of biological invasions in Brazil: a first assessment. NeoBiota 67:349–374. https://doi.org/10.3897/neobiota.67.59185

Alencar SM, Aguiar CL, Paredes-Guzmán J, Park YK (2005) Composição química de *Baccharis dracunculifolia*, fonte botânica das própolis dos estados de São Paulo e Minas Gerais. Ciência Rural 35:909–915

Allain L, Grace JB (2001) Changes in density and height of the shrub *Baccharis halimifolia* following burning in coastal tallgrass prairie. In: Proceedings of the 17th North American Prairie Conference. 66–72

Altesor A, Oesterheld M, Leoni E, Lezama F, Rodríguez C (2005) Effect of grazing on community structure and productivity of a Uruguayan grassland. Plant Ecol 179:83–91. https://doi.org/10.1007/s11258-004-5800-5

Amancio MB, Oki Y, Fernandes GW, Rago C, Goes-Neto A, Azevedo VAC (2021) Innovation and knowledge of prospective studies on the genus *Baccharis*. In *Baccharis*: from evolutionary and ecological aspects to social uses and medicinal applications. Springer International Publishing, Switzerland. pp 475–503. https://doi.org/10.1007/978-3-030-83511-8_19.

Avendaño D, Caballero M, Vázquez G (2021) Ecological distribution of *Stephanodiscus niagarae* Ehrenberg in central Mexico and niche modeling for its last glacial maximum habitat suitability in the Nearctic realm. J Paleolimnol 66:1–14. https://doi.org/10.1007/s10933-021-00178-w

Bacher S, Blackburn TM, Essl F, Genovesi P, Heikkilä J, Jeschke JM, Jones G, Keller R, Kenis M, Kueffer C, Martinou AF, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Richardson DM, Roy HE, Saul WC, Scalera R, Kumschick S (2018) Socio-economic impact classification of alien taxa (SEICAT). Methods Ecol Evol 9:159–168. https://doi.org/10.1111/2041-210X.12844

Barbosa NPU, Fernandes WW, Carneiro MAA, Júnior LAC (2010) Distribution of non-native invasive species and soil properties in proximity to paved roads and unpaved roads in a quartzitic mountainous grassland of southeastern Brazil (rupestrian fields). Biol Invasions 12(11):3745–3755. https://doi.org/10.1007/s10530-010-9767-y

Barbosa NPU, Fernandes GW, Sanchez-Azofeifa A (2015) A relict species restricted to a quartzitic mountain in tropical America: An example of microrefugium? Acta Botanica Brasílica 29:299–309. https://doi.org/10.1590/0102-33062014abb3731

Bazzichetto M, Malavasi M, Bartak V, Acosta ATR, Rocchini D, Carranza ML (2018) Plant invasion risk: a quest for invasive species distribution modelling in managing protected areas. Ecol Ind 95:311–319. https://doi.org/10.1016/j.ecolind.2018.07.046

Blackburn TM, Duncan RP (2001) Determinants of establishment success in introduced birds. Nature 414:195–197. https://doi.org/10.1038/35102557

Calleja F, Ondiviela B, Juanes JA (2019a) Invasive potential of *Baccharis halimifolia*: experimental characterization of its establishment capacity. Environ Exp Bot 162:444–454. https://doi.org/10.1016/j.envexpbot.2019.03.020

Calleja F, Ondiviela B, Galván C, Recio M, Juanes JA (2019b) Mapping estuarine vegetation using satellite imagery: the case of the invasive species *Baccharis halimifolia* at a Natura 2000 site. Cont Shelf Res 174:35–47. https://doi.org/10.1016/j.csr.2019.01.002

Caño L, García-Magro D, Herrera M (2013) Phenology of the dioecious shrub Baccharis halimifolia along a salinity gradient: consequences for the invasion of Atlantic subhalophilous communities. Plant Biosyst 147:1128–1138. https://doi.org/10.1080/11263504.2013.861537

Caño L, Campos JA, García-Magro D (2012) Replacement of estuarine communities by an exotic shrub: distribution and invasion history

of *Baccharis halimifolia* in Europe. Biol Invasions 15:1183–1188. https://doi.org/10.1007/s10530-012-0360-4

Caño L, Campos JA, García-Magro D, Herrera M (2014) Invasiveness and impact of the non-native shrub Baccharis halimifolia in sea rush marshes: fine-scale stress heterogeneity matters. Biol Invasions 16:2063–2077. https://doi.org/10.1007/s10530-014-0648-7

Caño L, Fuertes-Mendizabal T, García-Baquero G, Herrera M, Begoña González-Moro MB (2016) Plasticity to salinity and transgenerational effects in the nonnative shrub Baccharis halimifolia: insights into an estuarine invasion. Am J Bot 103:808–820. https://doi.org/10.3732/ajb.1500477

Carrol SP, Klassen SP, Dingle H (1998) Rapidly evolving adaptations to host ecology and nutrition in the soapberry bug. Evol Ecol 12:955–968. https://doi.org/10.1023/A:1006568206413

CGIAR (2021) Spatial downscaling Data. www.ccafs-climate.org/data_spatial_downscaling. Accessed on 09 May 2021

Cobos ME, Townsend Peterson A, Barve N, Osorio-Olvera L (2019) Kuenm: an R package for detailed development of ecological niche models using Maxent. PeerJ 2:1–15. https://doi.org/10.7717/peerj.6281

Committee on the Scientific Basis for Predicting the Invasive Potential of Non-indigenous Plants and Plant Pests in the United States (2002) Predicting Invasions of Non-indigenous Plants and Plant Pests. Washington, National Academy Press. https://www.ncbi.nlm.nih.gov/books/NBK207526 doi:https://doi.org/10.17226/10259. Accessed on 09 May 2021

Crystal-Ornelas R, Hudgins EJ, Cuthbert RN, Haubrock PJ, Fantle-Lepczyk J, Angulo E, Kramer AM, Ballesteros-Mejia L, Leroy B, Leung B, López-López E, Diagne C, Courchamp F (2021) Economic costs of biological invasions within North America. NeoBiota 67:485–510. https://doi.org/10.3897/neobiota.67.58038

Darwin C (1859) The origin of species (reprinted 1958). Mentor Books, New York, p 479

Davis SD, Mooney HA (1985) Comparative water relations of adjacent California shrub and grassland communities. Oecologia 66:522–529. https://doi.org/10.1007/BF00379344

Duarte A, Whitlock SL, Peterson JT (2018) Species distribution modeling. Encyclop Ecol 6:189–198. https://doi.org/10.1016/B978-0-12-409548-9.10572-X

Dukes JSS, Mooney HA (1999) Does global change increase the success of biological invaders? Trends Ecol Evol 14:135–139. https://doi.org/10.1016/S0169-5347(98)01554-7

Duncan RP, Bomford M, Forsyth DM, Conibear L (2001) High predictability in introduction outcomes and the geographical range size of introduced Australian birds: a role for climate. J Anim Ecol 70:621–632. https://doi.org/10.1046/j.1365-2656.2001.00517.x

Elith J, Graham CH, Anderson RP, Dudik M, Ferrier S, Guisan A, Hijmans RJ, Huettmann F, Leathwick JR, Lehmann A, Li J, Lohmann LG, Loiselle BA, Manion G, Moritz C, Nakamura M, Nakazawa Y, Overton JMM, Peterson AT, Phillips SJ, Richardson K, Scachetti-Pereira R, Schapire REE, Soberón J, Williams S, Wisz MS, Zimmermann NE (2006) Novel methods improve prediction of species' distributions from occurrence data. Ecography 29:129–151. https://doi.org/10.1111/j.2006.0906-7590.04596.x

Elith J (2017) Predicting distributions of invasive species. In: Invasive species: risk assessment and management. Cambridge University Press, United Kingdom

Elith J, Phillips SJ, Hastie T, Dudik M, Chee YE, Yates CJ (2011) A statistical explanation of MaxEnt for ecologists. Divers Distrib 17:43–57. https://doi.org/10.1111/j.1472-4642.2010.00725.x

Escobar LE, Lira-Noriega A, Medina-Vogel G, Townsend Peterson A (2014) Potential for spread of the white-nose fungus (*Pseudogymnoascus destructans*) in the Americas: use of Maxent and NicheA to assure strict model transference. Geospat Health 9:221–229. https://doi.org/10.4081/gh.2014.19

Espírito-Santo MM, Madeira BG, Neves FS, Faria ML, Fagundes M, Fernandes GW (2003) Sexual differences in reproductive phenology and their consequences for the demography of *Baccharis dracunculifolia* (Asteraceae), a dioecious tropical shrub. Ann Bot 91:13–19. https://doi.org/10.1093/aob/mcg001

Estay SA, Labra FA, Sepulveda RD, Bacigalupe LD (2014) Evaluating habitat suitability for the establishment of *Monochamus* spp. through climate-based niche modeling. PLoS ONE 9:1–7. https://doi.org/10.1371/journal.pone.0102592

Fagundes M, Fernandes GW (2011) Insect herbivores associated with *Baccharis dracunculifolia* (Asteraceae): responses of gall-forming and free-feeding insects to latitudinal variation. Rev Biol Trop 59:1419–1432

Fagundes M, Faria ML, Fernandes GW (2001) Efeitos da distribuição de *Baccharis dracunculifolia* (Asteraceae) na abundância e no parasitismo de galhas *de Neopelma baccharidis* (Homoptera: Psylidae). Unimontes Científica 1:97–103

Fagundes M, Neves FS, Fernandes GW (2005) Direct and indirect interactions involving ants, insect herbivores, parasitoids, and the host plant *Baccharis dracunculifolia* (Asteraceae). Ecol Entomol 30:28–35. https://doi.org/10.1111/j.0307-6946.2005.00668.x

Fantle-Lepczyk JE, Haubrock PJ, Kramer AM, Cuthbert RN, Turbelin AJ, Crystal-Ornelas R, Diagne C, Courchamp F (2022) Economic costs of biological invasions in the United States. Sci Total Environ 806:151318. https://doi.org/10.1016/j.scitotenv.2021.151318

Faria J, Prestes ACL, Moreu I, Cacabelos E, Martins GM (2022) Dramatic changes in the structure of shallow-water marine benthic communities following the invasion by Rugulopteryx okamurae (Dictyotales, Ochrophyta) in Azores (NE Atlantic). Mar Pollut Bull 175:113358. https://doi.org/10.1016/j.marpolbul.2022.113358

Feng X, Park DS, Walker C, Peterson AT, Merow C, Papeş M (2019) A checklist for maximizing reproducibility of ecological niche models. Nat Ecol Evol 3:1382–1395. https://doi.org/10.1038/s41559-019-0972-5

Fernandes GW, Oki Y, Barbosa M (2021) Baccharis: from evolutionary and ecological aspects to social uses and medicinal applications. Springer International Publishing, Switzerland. https://doi.org/10.1007/978-3-030-83511-8_1

Fernandes GW, Oki Y, Belmiro MS, Resende FM, Correa-Jr A, Azevedo JR (2018) Multitrophic interactions among fungal endophytes, bees, and *Baccharis dracunculifolia*: resin tapering for propolis production leads to endophyte infection. Arthropod-Plant Interact 12:329–337. https://doi.org/10.1007/s11829-018-9597-x

Ficetola GF, Thuiller W, Miaud C (2007) Prediction and validation of the potential global distribution of a problematic alien invasive species – the American bullfrog. Divers Distrib 13:476–485. https://doi.org/10.1111/j.1472-4642.2007.00377.x

Fick SE, Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int J Climatol 37:4302–4315. https://doi.org/10.1002/joc.5086

Fitzpatrick MC, Weltzin JF, Sanders NJ, Dunn RR (2007) The biogeography of prediction error: Why does the introduced range of the fire ant over-predict its native range? Glob Ecol Biogeogr 16:24–33. https://doi.org/10.1111/j.1466-8238.2006.00258.x

Forsyth DM, Duncan RP, Bomford M, Moore G (2004) Climatic suitability, life-history traits, introduction effort, and the establishment and spread of introduced mammals in Australia. Conserv Biol 18:557–569. https://doi.org/10.1111/j.1523-1739.2004.00423.x

Fried G, Caño L, Brunel S, Beteta E, Charpentier A, Herrera M, Starfinger U, Dane Panetta F (2016) Monographs on invasive plants in Europe: *Baccharis halimifolia* L. Botany Letters 163:127–153. https://doi.org/10.1080/23818107.2016.1168315

GBIF (2021) *Baccharis dracunculifolia* DC. GBIF Occurrence data. www.gbif.org/occurrence/download/0271834-2006130841 48143. Accessed on 09 May 2021

Gerlach JD (2000) A model experimental system for predicting the invasion success and ecosystem impacts of non-indigenous summer-flowering annual plants in California' 's Central Valley grasslands and oak woodlands. PhD dissertation, University of California, Davis, CA

Giovanelli JGR, Araújo CO, Haddad CFB, Alexandrino J (2008a) Modelagem do nicho ecológico de *Phyllomedusa ayeaye* (Anura: Hylidae): previsão de novas áreas de ocorrência para uma espécie rara. Neotrop Biol Conserv 3:59–65

Giovanelli JGR, Haddad CFB, Alexandrino J (2008b) Predicting the potential distribution of the alien invasive American bullfrog (*Lithobates catesbeianus*) in Brazil. Biol Invasions 10:585–590. https://doi.org/10.1007/s10530-007-9154-5

Gomes V, Fernandes GW (2002) Germinação de aquênios de *Baccharis dracunculifolia* D. C. (Asteraceae). Acta Botanica Brasilica 16:421–427. https://doi.org/10.1590/S0102-3306200200 0400005

Gong X, Chen Y, Wang T, Jiang X, Hu X, Feng J (2020) Double-edged effects of climate change on plant invasions: ecological niche modeling global distributions of two invasive alien plants. Sci Total Environ 740:139933. https://doi.org/10.1016/j.scitotenv.2020.139933

Grace J (1987) Climatic tolerance and the distribution of plants. New Phytol 106:113–130. https://doi.org/10.1111/j.1469-8137.1987.tb04686.x

Grant SNC (2020) Field Museum of Natural History (Botany) Seed Plant Collection. Version 11.12. Field Museum. Occurrence dataset. GBIF. Accessed on 09 May 2022

Heiden G (2021) Baccharis: diversity and distribution. In: Fernandes GW, Oki Y, Barbosa M (eds) Baccharis: from evolutionary and ecological aspects to social uses and medicinal applications. Springer, pp 23–80. https://doi.org/10.1007/978-3-030-83511-8_2

Hernandez PA, Graham CH, Máster LL, Albert DL (2006) The effect of sample size and species characteristics on performance of different species distribution modeling methods. Ecography 29:773–785. https://doi.org/10.1111/j.0906-7590.2006.04700.x

Hijmans RJ (2021) Geographic data analysis and modeling [R package raster version 3.4-10]. Hobbs RJ, Mooney HA 1986. Community changes following shrub invasion of grassland. Oecologia 70:508–513. https://doi.org/10.1007/BF00379896

Hirzel AH, Le Lay G (2008) Habitat suitability modelling and niche theory. J Appl Ecol 45:1372–1381. https://doi.org/10.1111/j.1365-2664.2008.01524.x

Jiménez-Valverde A, Peterson AT, Soberón J, Overton JM, Aragón P, Lobo JM (2011) Use of niche models in invasive species risk assessments. Biol Invasions 13:2785–2797. https://doi.org/10.1007/s10530-011-9963-4

Kaufmann RK, Kauppi H, Mann ML, Stock JH (2011) Reconciling anthropogenic climate change with observed temperature 1998–2008. Proc Natl Acad Sci USA 108:11790–11793. https://doi.org/10.1073/pnas.1102467108

Kearney M, Phillips BL, Tracy CR, Christian KA, Betts G, Porter WP (2008) Modelling species distributions without using species distributions: the Cane Toad in Australia under current and future climates. Ecography 31:423–434. https://doi.org/10.1111/j.0906-7590.2008.05457.x

Koch RL, Venette RC, Hutchison WD (2006) Invasions by *Harmonia axyridis* (Pallas) in the Western Hemisphere: implications for South America. Neotrop Entomol 35:421–434

Kornas J (1990) Plant invasions in central Europe: historical and ecological aspects. In: di Castri F, Hansen AJ, Debussche M Biological invasions in Europe and the Mediterranean basin. Dordrecht,

Kluwer Academic Publishers, pp 19–36. https://doi.org/10.1007/978-94-009-1876-4_2

Kuhn M, Wing J, Weston S, Williams A, Keefer C, Engelhardt A, Cooper T, Mayer Z, Kenkel B, Team RC (2020) Package 'caret' The R Journal. 223: 1–7

Lázaro-Lobo A, Ervin G, Caño L, Panetta D (2021) Biological invasions by *Baccharis*. In *Baccharis*: from evolutionary and ecological aspects to social uses and medicinal applications, edited by Fernandes GW, Oki Y, Barbosa M Springer International Publishing, Switzerland. pp 185–214. https://doi.org/10.1007/978-3-030-83511-8_8

Levine JM, Vilà M, D'Antonio CM, Dukes JS, Grigulis K, Lavorel S (2003) Mechanisms underlying the impacts of exotic plant invasions. Proc Royal Soc B Biol Sci 270:775–781. https://doi.org/10.1098/rspb.2003.2327

Loayza I, Abujder D, Aranda R, Jakupovic J, Colin G, Deslauriers H, Jean F (1995) Essential oils of *Baccharis salicifolia*, *B. latifolia* and *B. dracunculifolia*. Phytochemistry 38:381–389. https://doi.org/10.1016/0031-9422(94)00628-7

Lockwood JL, Cassey P, Blackburn T (2005) The role of propagule pressure in explaining species invasions. Trends Ecol Evol 20:223–228. https://doi.org/10.1016/j.tree.2005.02.004

Lorenzi H (1991) Plantas daninhas do Brasil: terrestres, aquáticas, parasitas, tóxicas e medicinais. Nova Odessa, Editora Plantarum, pp 440

Ludsin SA, Wolfe AD (2001) Biological invasion theory: Darwin's contributions from the origin of species. Bioscience 51:780–789. https://doi.org/10.1641/0006-3568(2001)051[0780:BITDSC]2.0.CO;2

Malacrinò A, Sadowski VA, Martin TK, De Oliveira NC, Brackett IJ, Feller JD, Harris KJ, Heredia OC, Vescio R, Bennett AE (2020) Biological invasions alter environmental microbiomes: a meta-analysis. PLoS ONE 15:1–12. https://doi.org/10.1371/journal.pone.0240996

Marques AR, Fernandes GW, Reis IA, Assunção RM (2002) Distribution of adult male and female Baccharis concinna (Asteraceae) in the rupestrian fields of Serra Do Cipó, Brazil. Pl Biol 4(1):94–103. https://doi.org/10.1055/s-2002-20441

Minteguiaga M, González A, Catalán CAN, Dellacassa E (2021) Relationship between *Baccharis dracunculifolia* DC. And *B. microdonta* DC. (Asteraceae) by their different seasonal volatile expression. Chem Biodivers 18:1–6. https://doi.org/10.1002/cbdv.202100064

Mooney HA, Hobbs RJ (1986) Resilience at the individual plant level. In: Dell B, Hopkins AJM, Lamont BB Resilience in Mediterranean-type ecosystems. Dordrecht, Kluwer Academic Publishers, 16: 65–82. https://doi.org/10.1007/978-94-009-4822-8_5

Mooney HA, Bullock SH, Medina E (1995) Seasonally dry tropical forests. Cambridge University Press, Cambridge

Muscarella R, Galante PJ, Soley-Guardia M, Boria RA, Kass JM, Uriarte M, Anderson RP (2014) ENMeval: an R package for conducting spatially independent evaluations and estimating optimal model complexity for Maxent ecological niche models. Methods Ecol Evol 5:1198–1205. https://doi.org/10.1111/2041-210x.12261

Navarro-Racines C, Tarapues J, Thornton P, Jarvis A, Ramirez-Villegas J (2020) High-resolution and bias-corrected CMIP5 projections for climate change impact assessments. Sci Data 7:1–14. https://doi.org/10.1038/s41597-019-0343-8

Nyári A, Ryall C, Peterson AT (2006) Global invasive potential of the house crow *Corvus splendens* based on ecological niche modelling. J Avian Biol 37:306–311. https://doi.org/10.1111/j.2006.0908-8857.03686.x

Obiakara MC, Etaware PM, Chukwuka KS (2020) Maximum entropy niche modelling to estimate the potential distribution of

phytophthora megakarya brasier & M. J. Griffin (1979) in tropical regions. Eur J Ecol 6:23–40

Oliveira FIS, Oki Y, Resende FM, Angrisano P, Rosa DCP, Arantes-Garcia L, Fernandes GW (2021) From innovation to market: an analysis of the propolis production chain. In: Fernandes, G.W.; Oki, Y. & Barbosa, M. (editors) Springer International Publishing, Switzerland. https://doi.org/10.1007/978-3-030-83511-8_23

Oshea P (2021) Rspatial: spatial thinning and more (0.3.0). Github. https://github.com/oshea-patrick/RSpatial. Accessed on 09 May 2022

Owens HL, Campbell LP, Dornak LL, Saupe EE, Barve N, Soberón J, Ingenloff K, Lira-Noriega A, Hensz CM, Myers CE, Peterson AT (2013) Constraints on interpretation of ecological niche models by limited environmental ranges on calibration areas. Ecol Model 263:10–18. https://doi.org/10.1016/j.ecolmodel.2013.04.011

Pacifici M, Foden WB, Visconti P, Watson JEM, Butchart SHM, Kovacs KM, Scheffers BR, Hole DG, Martin TG, Akçakaya HR, Corlett RT, Huntley B, Bickford D, Carr JA, Hoffmann AA, Midgley GF, Pearce-Kelly P, Pearson RG, Williams SE, Rondinini C (2015) Assessing species vulnerability to climate change. Nat Clim Chang 5:215–225. https://doi.org/10.1038/nclimate2448

Papes M, Peterson AT (2003) Predicting the potential invasive distribution for *Eupatorium adenophorum* Spreng. in China. J Wuhan Bot Res 21:137–142

Parolo G, Rossi G, Ferrarini A (2008) Toward improved species niche modelling: Arnica montana in the Alps as a case study. J Appl Ecol 45:1410–1418. https://doi.org/10.1111/j.1365-2664.2008.01516.x

Paudel S, Battaglia LL (2013) Germination responses of the invasive triadica sebifera and two co-occurring native woody species to elevated salinity across a Gulf Coast transition ecosystem. Wetlands 33(3):527–535. https://doi.org/10.1007/s13157-013-0410-4

Pearson RG, Dawson TP (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? Glob Ecol Biogeogr 12:361–371. https://doi.org/10.1046/j.1466-822X.2003.00042.x

Pearson RG, Raxworthy CJ, Nakamura M, Peterson AT (2007) Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. J Biogeogr 34:102–117. https://doi.org/10.1111/j.1365-2699.2006.01594.x

Peterson AT, Vieglais DA (2001) Predicting species invasions using ecological niche modeling: new approaches from bioinformatics attack a pressing problem. Bioscience 51:363–371. https://doi.org/10.1641/0006-3568(2001)051[0363:PSIUEN]2.0.CO;2

Peterson AT (2006) Uses and requirements of ecological niche models and related distributional models. Biodiver Inform 3:59–72

Peterson AT, Scachetti-Pereira R, Kluza DA (2003) Assessment of invasive potential of *Homalodisca coagulata* in western North America and South America. Biota Neotrop 3:1–7

Peterson AT, Soberón J, Sánchez-Cordero V (1999) Conservatism of ecological niches in evolutionary time. Science 285:1265–1267. https://doi.org/10.1126/science.285.5431.1265

Phillips SJ, Anderson RP, Schapire REE (2006) Maximum entropy modeling of species geographic distributions. Ecol Model 190:231–259. https://doi.org/10.1016/j.ecolmodel.2005.03.026

Phillips SJ, Anderson RP, Dudík M, Schapire RE, Blair ME (2018) Opening the black box: an open-source release of Maxent. Ecography 40(7):887–893. https://doi.org/10.1111/ecog.03049

Pyšek P, Pyšek A (1995) Invasion by *Heracleum mantegazzianum* in different habitats in the Czech Republic. J Veg Sci 6:711–718. https://doi.org/10.2307/3236442

Pyšek P (2003) Czech alien flora and the historical pattern of its formation: What came first to central Europe? Oecologia 135:122–130. https://doi.org/10.1007/s00442-002-1170-7

Pyšek P, Hulme PE, Simberloff D, Bacher S, Blackburn TM, Carlton JT, Dawson W, Essl F, Foxcroft LC, Genovesi P, Jeschke JM, Kühn I, Liebhold AM, Mandrak NE, Meyerson LA, Pauchard A, Pergl J, Roy HE, Seebens H, Richardson DM (2020) Scientists' warning on invasive alien species. Biol Rev 95:1511–1534. https://doi.org/10.1111/brv.12627

Qiao H, Escobar LE, Peterson TA (2017) Accessible areas in ecological niche comparisons of invasive species: recognized but still overlooked. Sci Rep 7:1–9. https://doi.org/10.1038/s41598-017-01313-2

Qiao H, Peterson AT, Campbell LP, Soberón J, Ji L, Escobar LE (2016) NicheA: creating virtual species and ecological niches in multivariate environmental scenarios. Ecography 39:805–813. https://doi.org/10.1111/ecog.01961

R Core Team (2021) R: a language and environment for statistical computing. https://www.r-project.org/ Accessed on 09 May 2022

Raghavan RK, Heath ACG, Lawrence KE, Ganta RR, Peterson AT, Pomroy WE (2020) Predicting the potential distribution of Amblyomma americanum (Acari: Ixodidae) infestation in New Zealand, using maximum entropy-based ecological niche modelling. Exp Appl Acarol 80:227–245. https://doi.org/10.1007/s10493-019-00460-7

Raxworthy C, Martinez-Meyer E, Horning N, Nussbaum R, Schneider G, Ortega-Huerta MA, Peterson AT (2003) Predicting distributions of known and unknown reptile species in Madagascar. Nature 426:837–841. https://doi.org/10.1038/nature02205

Reichard SH, White P (2009) Horticulture as a pathway of invasive plant introductions in the United States. Bioscience 51:103–113. https://doi.org/10.1641/0006-3568(2001)051[0103:HAAPOI]2.0.CO;2

Richardson DM, Thuiller W (2007) Home away from home – objective mapping of high-risk source areas for plant introductions. Divers Distrib 13:299–323. https://doi.org/10.1111/j.1472-4642.2007.00337.x

Rodda GH, Jarnevich CS, Reed RN (2011) Challenges in identifying sites climatically matched to the native ranges of animal invaders. PLoS ONE 6:e14670. https://doi.org/10.1371/journal.pone.0014670

Saunders SP, Michel NL, Bateman BL, Wilsey CB, Dale K, LeBaron GS, Langham GM (2020) Community science validates climate suitability projections from ecological niche modeling. Ecol Appl 30:1–17. https://doi.org/10.1002/eap.2128

Schmidt KA, Whelan CJ (1999) Effects of exotic *Lonicera* and *Rhamnus* on songbird nest predation. Conserv Biol 13:1502–1506. https://doi.org/10.1046/j.1523-1739.1999.99050.x

Schrag AM, Bunn AG, Graumlich LJ (2008) Influence of bioclimatic variables on treeline conifer distribution in the Greater Yellowstone Ecosystem: implications for species of conservation concern. J Biogeogr 35:698–710. https://doi.org/10.1111/j.1365-2699.2007.01815.x

Sequeira AMM, Bouchet PJ, Yates KL, Mengersen K, Caley MJ (2018) Transferring biodiversity models for conservation: opportunities and challenges. Methods Ecol Evol 9:1250–1264. https://doi.org/10.1111/2041-210X.12998

Steven JP, Miroslav D, Robert ES (2021) Maxent software for modeling species niches and distributions (Version 3.4.1). http://biodiversityinformatics.amnh.org/open_source/maxent/. Accessed on May 08 2021

Thapa S, Chitale V, Rijal SJ, Bisht N, Shrestha BB (2018) Understanding the dynamics in distribution of invasive alien plant species under predicted climate change in Western Himalaya. PLoS ONE 13:1–16. https://doi.org/10.1371/journal.pone.0195752

Thorn JS, Nijman V, Smith D, Nekaris KAI (2009) Ecological niche modelling as a technique for assessing threats and setting conservation priorities for Asian slow lorises (Primates: Nycticebus).

Divers Distrib 15:289–298. https://doi.org/10.1111/j.1472-4642.2008.00535.x

Valéry L, Hervé F, Jean-Claude L, Daniel S (2009) Invasive species can also be native. Trends Ecol Evol 24:585–586. https://doi.org/10.1016/j.tree.2009.07.003

Vivrette NJ, Muller CH (1977) Mechanism of invasion and dominance of coastal grassland by *Mesembryanthenum crystallinum*. Ecol Monogr 47:301–318. https://doi.org/10.2307/1942519

Von der Lippe M, Kowarik I (2008) Do cities export biodiversity? Traffic as dispersal vector across urban–rural gradients. Divers Distrib 14:18–25. https://doi.org/10.1111/j.1472-4642.2007.00401.x

Werneck FP, Costa GC, Colli GR, Prado DE, Sites JW (2010) Revisiting the historical distribution of seasonally dry tropical forests: new insights based on paleodistribution modelling and palynological evidence. Glob Ecol Biogeogr 20:272–288. https://doi.org/10.1111/j.1466-8238.2010.00596.x

Westman WE, Panetta FD, Stanely TD (1975) Ecological studies on reproduction and establishment of the woody weed, groundsel bush (Baccharis halimifolia L.: Asteraceae). Australian J Agricult Res 26(5):855–870. https://doi.org/10.1071/AR9750855

Williams K, Hobbs RJ, Hamburg SP (1987) Invasion of an annual grassland in Northern California by *Baccharis pilularis* ssp. Consanguinea Oecologia 72:461–465. https://doi.org/10.1007/BF00377580

Williamson M, Fitter A (1996) The characters of successful invaders. Biol Cons 78:163–170. https://doi.org/10.1016/0006-3207(96)00025-0

WorldClim (2021) Historical climate data. https://www.worldclim.org/data/worldclim21.html. Accessed on 09 May 2021

Zar JH (1996) Biostatistical analysis. Prentice Hall, New Jersey, p 944

Zavaleta ES (2005) Shrub establishment under experimental global changes in a California grasslands. Plant Ecol 184:53–63

Zenni RD, Essl F, García-Berthou E, McDermott SM (2021) The economic costs of biological invasions around the world. NeoBiota 67:1–9. https://doi.org/10.3897/neobiota.67.69971

Zhang H, Song J, Zhao H, Li M, Han W (2021) Predicting the distribution of the invasive species *leptocybe invasa*: combining Maxent and geodetector models. Insects 12:1–18. https://doi.org/10.3390/insects12020092

Zimmermann NE, Edwards TC, Graham CH, Pearman PB, Svenning JC (2010) New trends in species distribution modelling. Ecography 33:985–989. https://doi.org/10.1111/j.1600-0587.2010.06953.x

Zwiener VP, Lira-Noriega A, Grady CJ, Padial AA, Vitule JRS (2018) Climate change as a driver of biotic homogenization of woody plants in the Atlantic Forest. Glob Ecol Biogeogr 27:298–309. https://doi.org/10.1111/geb.12695

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.