

Forthcoming risk of *Prosopis juliflora* global invasion triggered by climate change: implications for environmental monitoring and risk assessment

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Abstract Climate is a determinant factor in species distribution and climate change will affect the species abilities to occupy geographic regions. *Prosopis juliflora* is one of the most problematic invasive species and its biological invasion causes various negative effects in tropical, arid, and semi-arid regions of the world. As eradication efforts subsequent to the establishment of an alien invasive species are costly and time-consuming, assessing patterns of the introduction of an invasive species to new regions is among the most cost-effective means of monitoring and management of natural ecosystems. In this study by using the concept of species distribution modeling (SDM) and maximum entropy (MaxEnt) method, the effect of climate change on the current and future distribution of *P. juliflora* has been assessed at a global scale. Bioclimatic variables in current condition and 2050 regarding two global circulation models (GCM) and two climate change scenarios were considered as explanatory variables. Our results showed that annual mean temperature (BIO1), annual precipitation (BIO12), and temperature mean diurnal range (BIO2) represented more than 87% of the variations in the model, and with an AUC of 0.854 and TSS of 0.51, the model showed a good predictive performance. Our results indicate that on a global scale, suitable ranges for *P. juliflora* increase across all the GCM

and RCP scenarios. In a global scale, Mediterranean Basin, Middle East, and North America are regions with the highest risk of range expansion in the future. Regarding the negative impacts of *P. juliflora* on structure and function of natural habitats in the invaded areas, findings of this study could be considered as a warning appliance for the environmental monitoring of the regions highly sensitive to the global invasion of the species. We suggest that assessing impacts of climate change on the global distribution of the invasive species could be used as an efficient tool to implement broad-scale and priority-setting monitoring programs in natural ecosystems.

Keywords Mesquite · Alien species · Range expansion · MaxEnt · Biological invasion

Introduction

One of the most prominent manifestations of human activities on natural ecosystems is the introduction of exotic species into new habitats which is referred to as “biological invasion” (Vilà et al. 2011). The most salient impact of biological invasion is change in the normal functioning and structure of ecosystems (McCary et al.

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2016; Ehrenfeld 2010; Vilà et al. 2011) through reducing the ecological diversity of target habitats and homogenizing the biological structure of their respective animal and plant communities (Jeschke et al. 2014; Schirmel et al. 2016), increasing production and imposing change in food web (McCary et al. 2016; Zavaleta et al. 2001), and consequently through affecting ecosystem services and human communities (Pejchar and Mooney 2009).

On the other hand, climatic similarity between native and target areas has been identified as the most important prerequisite for a successful biological invasion and establishment (Scott and Panetta 1993; Thuiller et al. 2005). In many cases, invasive plants spread and establishment may be restricted due to the climatic dissimilarity between regions (Pyšek et al. 2003). Species climatic niche evolves very slowly due to the niche conservatism (Wiens et al. 2010). This has been an origin to develop species climatic niche based on the current distribution of the species and project it to new areas to find suitable habitats for the presence of the species (Guisan et al. 2013; Thuiller et al. 2005). Furthermore, producing highly accurate and large-scale climatic data and developing sophisticated statistical methods in relation to ecological niche modeling (ENM) have improved the ability to predict species distribution models (SDMs) and the invasion probability of numerous animal and plant species (Guisan and Thuiller 2005; Guisan et al. 2013).

Climate change is expected to substantially influence ecosystem biodiversity and processes as well as species phenology, genetic composition, distribution, and interactions (Scheffers et al. 2016; Franks et al. 2014). One of the most obvious effects of climate change on biodiversity is the projected change in species geographical ranges (Chen et al. 2011; Garcia et al. 2014). Over the past century, increasing evidence of climate change impacts on biodiversity patterns has been documenting a globally consistent rate of range shift in many species' geographic distributions (VanDerWal et al. 2013; Parmesan 2006). Nevertheless, treatments have mostly focused on native species as their conservation is the primary concern (Wang et al. 2014; Yousefi et al. 2015). Invasive species also show responses to climate change, and their responses have ecological and economic consequences. Inherent characteristics of many invasive plants, for example, their broad climatic tolerances and large geographic distribution (Hellmann et al. 2008; Qian and Ricklefs 2006), may influence their responses

to climate change. Short-time maturity and low seed mass are other characteristics that facilitate rapid range shifts of invasive plant species (Rejmánek and Richardson 1996). High phenotypic plasticity has widely been proposed as an important contributor to the invasive plant's success (Davidson et al. 2011). Moreover, climate change due to global warming will be favorable to species preferring warm and humid regions by offering them wider geographical extents in the future. This issue exacerbates the risk of invasive species dispersion and their consequent impacts on local communities (Pereira et al. 2010; Walther et al. 2002). Studies have shown that eradication efforts subsequent to the establishment of an alien invasive species are costly and time-consuming (Gallien et al. 2012; Genovesi 2005). Hence, predicting and preventing the introduction of alien invasive species to a specific region is viewed as the most important cost-effective means of monitoring and management of habitats and ecosystems (Broennimann and Guisan 2008; Thuiller et al. 2005). Therefore, an attempt is made in this research to evaluate the effect of climate change on the global distribution of mesquite tree (*Prosopis juliflora*) as one of the most problematic invasive species introduced to natural ecosystems. *P. juliflora* (family: Fabaceae) is known as an invader and has caused biodiversity loss and land use change in different parts of the world. This species has a wide evergreen canopy height ~ 14 m and is native to the Caribbean, Central, and North America. Rapid growth, nitrogen fixation, and tolerance to arid and semi-arid regions are among the most distinguishing characteristics of this species (Pasiiecznik et al. 2004). Mesquite develops a deep and strong root system, enabling the plant to tap underground water. The initial introduction of this species is most successful due to forming dense thickets, its palatability to livestock, and herbivores, as well as its high reproduction performance by producing up to 40 kg of seedpods and up to 60,000 seeds a year (Alban et al. 2002). Moreover, the plant's pod contains a high amount of sugar content which attracts herbivores who contribute to seed dispersal by eating and defecating the seeds into new locations. Environmental stressors such as drought improve the establishment of *P. juliflora* (Al-Rawahy et al. 2003) because this plant has a high seed viability and germination rate in the soil and takes advantage of changed conditions to occupy new areas and exert competition pressure on native species. Moreover, the allelopathic ability of *P. juliflora* to prevent other plants' seed

germination should also be taken into account (Shiferaw et al. 2004). Due to these abilities and characteristics, *P. juliflora* is a well-known invasive species in Australia, Africa, India, and other parts of the world (Aboud et al. 2005). It is recognized as one of the three most influential types of invaders in Ethiopia and Sudan in which state laws have been constructed and implemented to eradicate this species (Jama and Zeila 2005). In many arid and semi-arid regions of the world, the species invasion into high biodiversity riparian ecosystems is regarded as a serious threat (Geesing et al. 2004). Socioeconomic impacts of such an invasion on the livelihoods of local communities can also be very diverse; however, its adverse effects have been more reported in the literature (Mwangi and Swallow 2008).

In this research, the SDM analysis by using MaxEnt and focusing on climatic variables was performed to predict the present range and future distribution pattern of invasive American mesquite for 2050. MaxEnt is a machine-learning algorithm to predict the potential distribution (e.g., habitat suitability) of a species from presence data and independent environmental variables. Importantly, the MaxEnt method has been extensively used to investigate vulnerability of natural ecosystems to invasion by alien invasive species under current and future climate change scenarios (Fandohan et al. 2015; Kumar et al. 2015). Here, two global circulation models (GCMs) under two climatic scenarios were employed to derive an accurate estimate of changes in the invasion pattern of *P. juliflora*. Resulting from this research, it will be possible to delineate probable changes in the distribution pattern of invaded areas as well as areas prone to the invasion in the future in response to climate change. Furthermore, these findings can be used to direct management and prevention practices toward areas with the greatest risk of invasion.

Materials and methods

Occurrence points

The species occurrence points used to conduct SDM were obtained from a number of sources. We conducted a direct field sampling in Iran from 2016 to 2017 and also used data recorded by provincial bureaus of the Department of Environment. A total number of 225 presence points were obtained from our sampling efforts in Iran. Global distribution data were collected from the Global

Biodiversity Information Facility and scientific publications. Records with no GPS coordinates but exact locality names were georeferenced using Google Earth 7.1. For visual assessment and check spatial accuracy, all points were mapped using Diva-GIS v7.5 (R. Hijmans et al. 2012). Because of the probable spatial autocorrelation of the presence points, caused by different magnitudes and protocols of field sampling, we screened occurrence points to only one point within a 10-km radius buffer using ENMTools software (Warren et al. 2010). Overall, a total number of 1128 presence points from various parts of the world were gathered. Applying the screening pre-processing, 582 presence points (501 presence points from the entire global distribution and 81 presence points from Iran) were obtained for the SDM analysis. At the first look, our initial occurrence records might seem spatially biased toward better survey areas (for example native areas and Iran). Using two recommended strategies, spatial screening (Kramer-Schadt et al. 2013) and background weighting (explained below; Elith et al. 2010), helped us to perform a bias-adjusted model of *P. juliflora*'s global distribution.

MaxEnt and all correlative distribution models required background points, or pseudo-absence points, to fit the model (Phillips et al. 2006). Generally, MaxEnt randomly locates 10,000 background points in the whole extent of the environmental variables. Using random points within the area indicates that the occurrence points are a random sample from all locations where the species is present, which is unlikely because species points are from extant patches with suitable environments (Elith et al. 2010). Moreover, in terms of invasion modeling, there are areas with fewer records due to more recent invasions and/or areas that have been poorly sampled (Shabani et al. 2016). Elith et al. (2010) recommended to generate a weighting surface based on the density of presence point and allocate background points regarding the density of this map. This method reduces the bias raised from favoring points of heavily sampled areas over those from sparsely sampled areas (Shabani et al. 2016). To do this, firstly, a raster of kernel density of occurrence points was generated in ArcGIS. We then allocated 10,000 background points in the extent of environmental variables regarding the probability distribution of the kernel density map. We then fitted the MaxEnt model with this input which is known as sample with data (SWD). Figure 1 shows the global distribution of occurrence points and weighted background points.

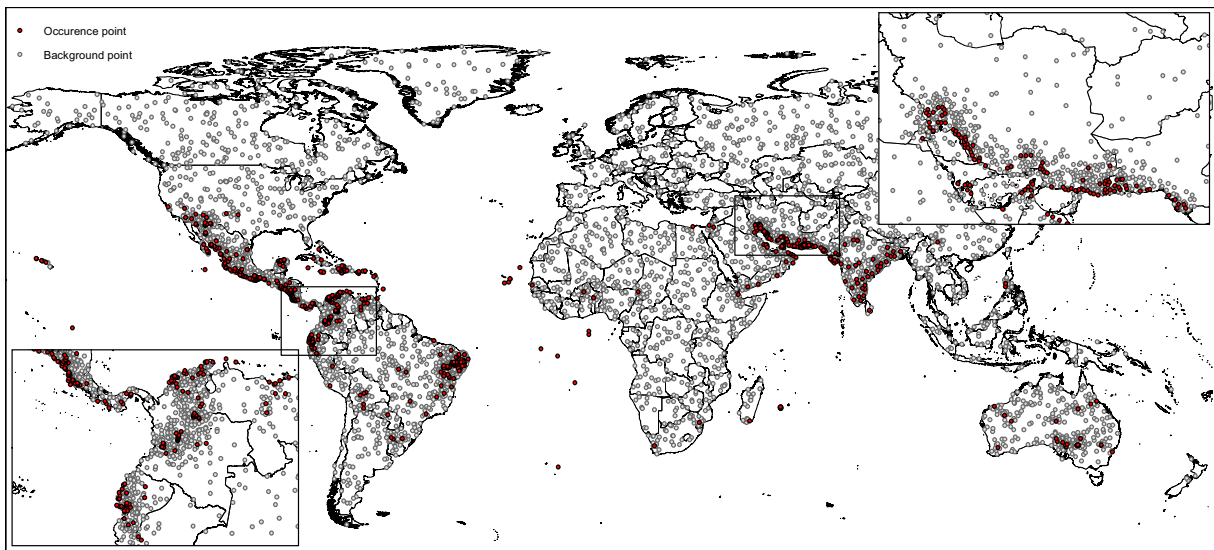


Fig. 1 Global distribution of presence points (red color) of *Prosopis juliflora* and background points (gray color) used to conduct current and future model of the biological invasion of the species

SDM procedure and climate change

SDM analysis was conducted using MaxEnt software v.3.3.3 (Phillips et al. 2006) and bioclimatic layers derived from WorldClim dataset (R. J. Hijmans et al. 2005) at a 2.5 arc-minute resolution. Generally, various statistical models have been developed to predict the distribution of a species (Elith et al. 2006). Beyond classical and simple regression methods (e.g. generalized linear models GLM), complex modeling based on machine learning, for example, artificial neural networks, maximum entropy, random forest, and booster regression trees, have widely been used in recent years (Franklin 2010). Among these, MaxEnt has been proved as specifically capable of handling complex interactions between response and predictor variables and to be robust to small sample sizes (Phillips et al. 2006; Wisz et al. 2008). MaxEnt works based on presence-background data rather than presence-absences data, and most importantly, does not undertake that background data precludes the probability of occurrence (Evangelista et al. 2008). This particularly makes MaxEnt a highly appropriate method for modeling the distribution of alien and invasive species as these species tend to establish and expand their range to new areas beyond their native distribution (Elith et al. 2010). Furthermore, its simplicity of use has made MaxEnt the most broadly used SDM algorithm. In November 2018, 9101 citations were reported in the

Web of Science for the article (Phillips et al. 2006) describing this method. Before the modeling, to avoid collinearity, the pairwise Pearson correlation coefficients between the variables were calculated and from those with a correlation coefficient greater than 0.75 one variable was selected for modeling. Accordingly, variables annual mean temperature (BIO1), mean diurnal range (BIO2), mean temperature of wettest quarter (BIO8), annual precipitation (BIO12), precipitation of driest month (BIO14), and precipitation seasonality (BIO15) were used to conduct the modeling approach. We used 75% of occurrence points to construct the model and the remaining 25% were used for validation. The importance of the climatic variables was determined using the Jackknife method and the model accuracy was examined based on the area under the curve (AUC) of the receiver operating characteristic (ROC) plot. To identify suitable cells from unsuitable ones, we converted continuous MaxEnt model to binary presence/absence map based on the threshold maximum training sensitivity plus specificity which is recommended by Liu et al. (2005) as a reliable threshold. Regarding this threshold, we also calculated sensitivity (percentage of presence points classified in the presence areas by the model) and specificity (percentage of background points classified in the absence areas by the model) to obtain the true statistic skill (TSS) of the model as follows: $TSS = \text{sensitivity} + \text{specificity} - 1$.

To assess the impact of climate change on the distribution of the species, future climate model for 2050 was conducted based on two global circulation models (GCM), including CCSM4 (Gent et al. 2011) and MIROC5 (Watanabe et al. 2010). These two GSMs are among the most commonly used models to assess the impact of climate change on biodiversity distribution. Using different GCMs also allowed us to assess the uncertainty from selecting GCMs as these differ clearly among regions (Flato et al. 2013). For each GCM, we considered two representative concentration pathways (RCPs), namely RCP 4.5 and RCP 8.5. By this, we included a moderate and an extreme greenhouse gas emission scenario in our analyses (Van Vuuren et al. 2011). To track changes in the potential distribution of the species, we calculated the percentage of cells gained or lost the climatic suitability for the two GCM models and the two RCPs compared to the current distribution of the species.

Results

Model performance based on AUC and TSS was 0.854 and 0.51, respectively, demonstrating that the MaxEnt model discriminated finely between presence points versus weighted background points. BIO1, BIO12, and BIO2 were identified as the most important variables in determining suitable habitats

for *P. juliflora* by explaining 59, 15.2, and 12.9% of the variation in the model, respectively, and 87% collectively. Figures 2 to 4 represent the worldwide climatic suitability for *P. juliflora* under the current and future climatic scenarios. According to the MaxEnt model, there are regions showing high suitability under current climatic conditions in all continents (Fig. 2); however, percentages of climatic suitable regions vary greatly (Table 1). Based upon the current climatic condition, we found low climatic suitable extent for *P. juliflora* in the northern hemisphere, while high suitability was predicted for near-equator regions in Africa, South America, and south of Asia.

Tracking the impacts of climate change on the distribution of the species revealed that on a global scale, suitable range sizes for *P. juliflora* increase across all the GCM and RCP scenarios (Table 1) (Fig. 3 and 4). In another word, the results showed that the projected range gain was greater than range loss across all climate change scenarios; however, the degree of projected range change varies between them. Totally, the potential range gain was projected to be 23.30–28.11%, while the range loss was projected to be 12.99–17.95%. As we expected, the highest increase in range size (i.e., range gain) was projected for extreme climate change scenarios (RCP 8.5) with 27.51% and 28.11% for CCSM and MIROC5, respectively.

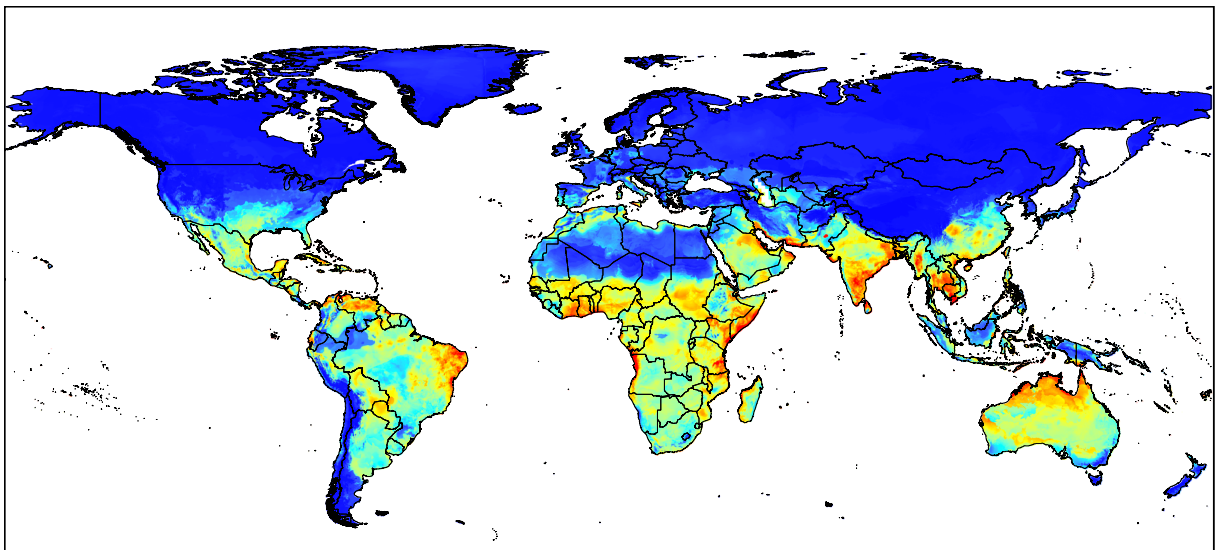


Fig. 2 World climatic suitability for *Prosopis juliflora* in current climatic conditions. Blue to red colors shows the gradient of suitability from low to high

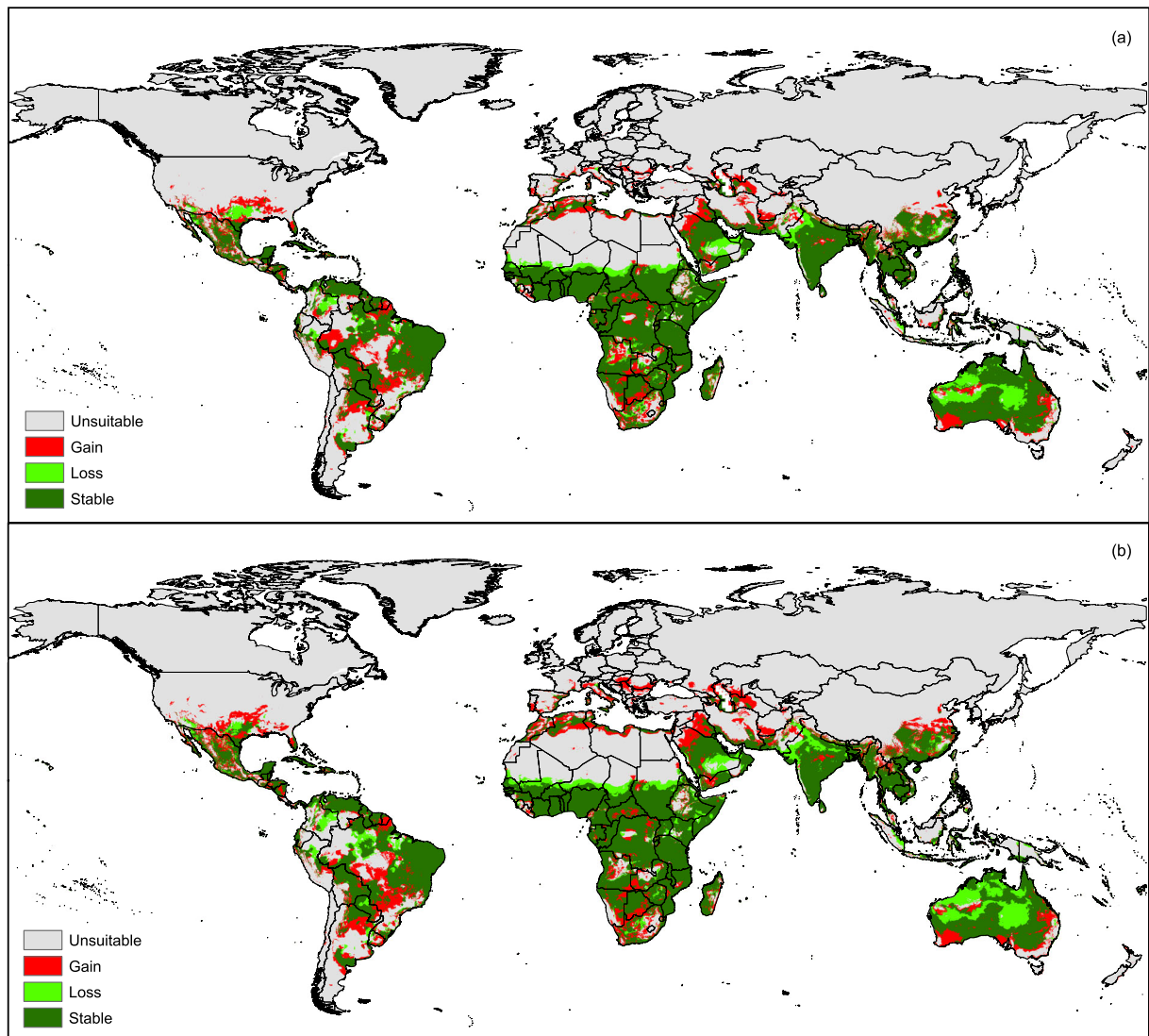


Fig. 3 Worldwide change in climatic suitability for *Prosopis juliflora* in 2050 based on CCSM4 global circulation model for RCP 4.5 (a) and RCP 8.5 (b)

On a continental scale, our SDM approach showed an increase in the extent of suitable habitats in the species' native range in South Africa, as well as for the invaded areas, except for Australia for which the range loss is projected to be greater than range gain (Table 1). We found that Europe is projected to gain extraordinary extent of suitable range (from 244 to 281%) for *P. juliflora* by 2050. North America showed the second-high magnitude of range gain (46.94–66.28%) followed by South America (24.25–30.62%), Asia (23.46–29.06%), and Africa (9–14.91%). Moreover, given a between-country comparison of gain/loss

range shifts, we found that some countries will experience a trade-off between habitat loss and gain while some other countries will be faced with either habitat loss or habitat gain (Figs. 5 and 6). According to these results, in almost all the studied climatic scenarios, the top ten countries with the highest absolute suitable habitat increase include Brazil, USA, China, Mexico, Iran, Iraq, Argentina, South Africa, Saudi Arabia, and Algeria. On the other hand, ten countries with the highest absolute suitable habitat decrease are Australia, Saudi Arabia, India, Sudan, Chad, Niger, Mali, Colombia, and Mexico.

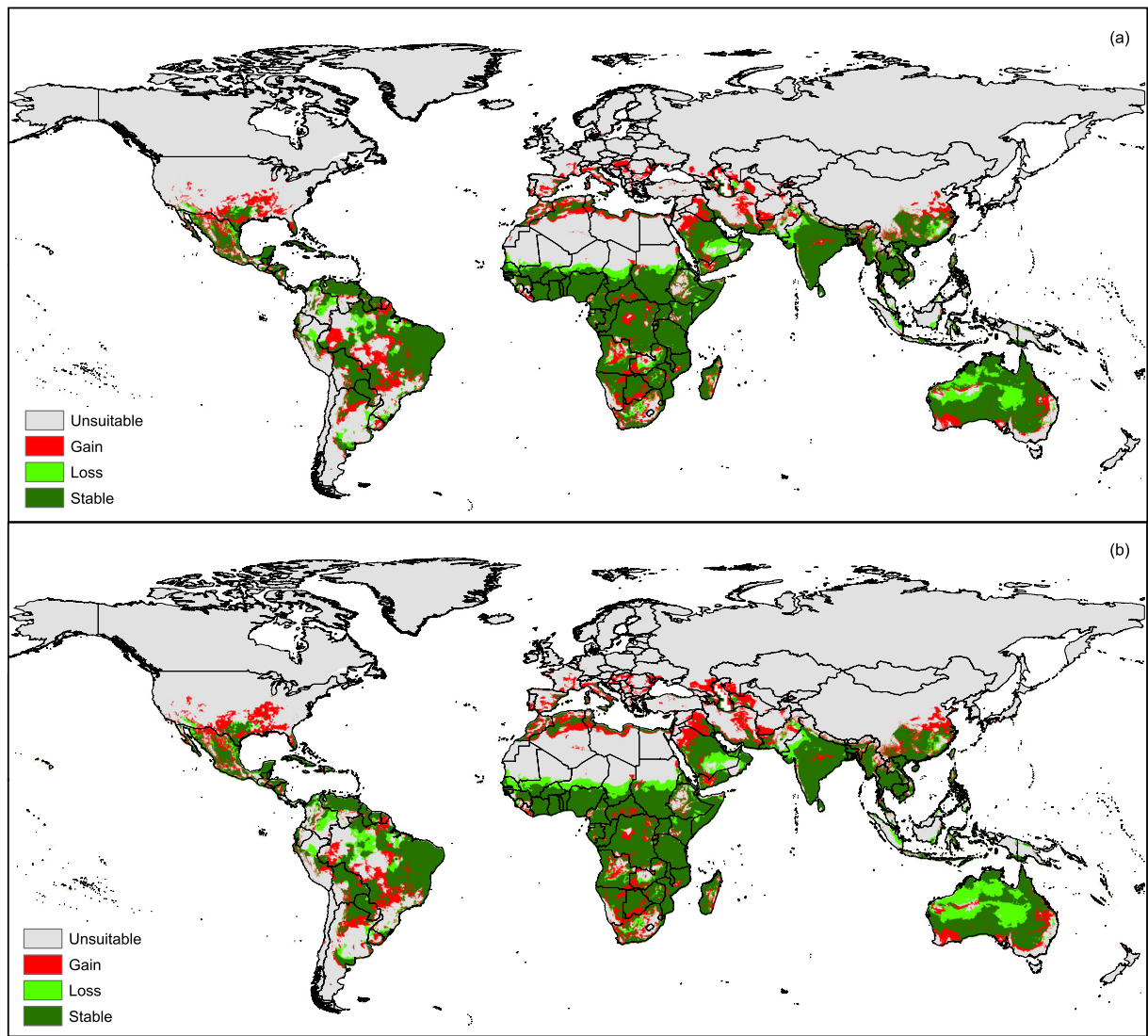


Fig. 4 Worldwide change in climatic suitability for *Prosopis juliflora* in 2050 based on MIROC5 global circulation model for RCP 4.5 (a) and RCP 8.5 (b)

Discussion

We used the concept of SDM to predict the distribution model of *P. juliflora* as an invasive species and to project it to current and future climate conditions. The projections were used to assess changes in the extent of occupation areas and identify areas facing with forthcoming invasion risks of the species. While several aspects influence a site’s susceptibility to a plant invasion, climate conditions seem to play main roles in global scale (Thuiller et al. 2005). Climate change often is in favor of invasive species due to worsening environmental conditions for indigenous species which undermine their

competitive power against invaders on ecosystem resources (Hellmann et al. 2008). Invasive species, on the other hand, have the inherent ability to tolerate wider environmental ranges or adapt to new environmental conditions (Vilà et al. 2011). This means that invasive species may experience a process of niche shift in new regions due to their inherent plasticity and the lack of their native competitors (Alexander and Edwards 2010; Broennimann and Guisan 2008). For example, Gallagher et al. (2010) have found that a large expansion of species introduced to Australia due to high plasticity, with c. 75% of target species facing novel biomes. Accordingly, as suggested in other studies (Broennimann and Guisan

Table 1 Changes in the geographic distribution of *Prosopis juliflora*

	Current vs CCSM 4.5		Current vs CCSM 8.5		Current vs MIROC 4.5		Current vs MIROC 8.5	
	Gain	Loss	Gain	Loss	Gain	Loss	Gain	Loss
Africa	14.91	9.55	15.3	11.92	13.88	9	14.76	9.48
Asia	23.46	12.68	29.06	13.23	21.63	11.8	27.09	13.95
Australia	9.79	18.81	10.77	26.47	11.8	19.25	12.55	25.1
Europe	244.96	0.66	251.75	0.84	275.03	6.27	281.06	6.04
North America	56.75	12.16	66.28	13.71	46.94	16.03	57.45	13.57
South America	24.25	15.37	24.7	12.97	29.05	8.66	30.62	12.26
Global	23.30	12.99	27.51	15.91	24.79	14.09	28.11	17.95

2008; Shabani and Kumar 2015), we used occurrence data of both native and invaded regions to develop the potential distribution of *P. juliflora*.

Our SDM analysis on global invasion risk of the species reveals large areas prone be colonized on several continents, but at different rates due to the different combination of scenarios and general circulation models. Based on the current climate SDM, our model indicates regions with suitable climatic conditions favoring invasion in native ranges, and regions where invasive populations already exist. Furthermore, our results highlight regions in the horn of Africa, Mediterranean ranges (e.g., north of Africa and south of Europe), and central and western Africa as highly vulnerable to potential invasion, as these regions show suitable climatic conditions for *P. juliflora* and are likely to be occupied by invasive populations. Further detailed research is expected to be carried out on the invasion risk of this species in countries which, based on the results of this study, will provide larger suitable areas due to climate change.

The success of invasive exotics in penetrating and establishing themselves in specific communities can be attributed to their superiority in relation to particular local indigenous species, in terms of a combination of measurable categories. Shiferaw et al. (2004) identified the dormancy, germination, and dispersal of the *P. juliflora* seed as the key botanical factors supporting its ability to establish in new areas (see also A El-Keblawy and Al-Rawai 2005). Its rapid reappearance and recovery after coppicing is an evidence of resilience that qualifies *P. juliflora* as a highly competitive invasive species (Shiferaw et al. 2004). Sharma and Dakshini (1998) reported the resultant substratum degradation due to the rapid growth and invasive spread of *P. juliflora* in semi-arid and arid regions in the north and north-west of India. The severe decline in soil pH, K, N, P, and organic matter content validates research into future *P. juliflora* distribution and the usefulness of such studies for farmers, soil scientists, and soil organizations (see Ali El-Keblawy and Al-Rawai 2007). Eradicating *P. juliflora* is thus likely to increase plant diversity in these soils.

Fig. 5 Area (based on the number of cells) of habitat loss and gain in countries with the highest changes based on CCMS RCP 4.5 (dark) and RCP 8.5 (gray)

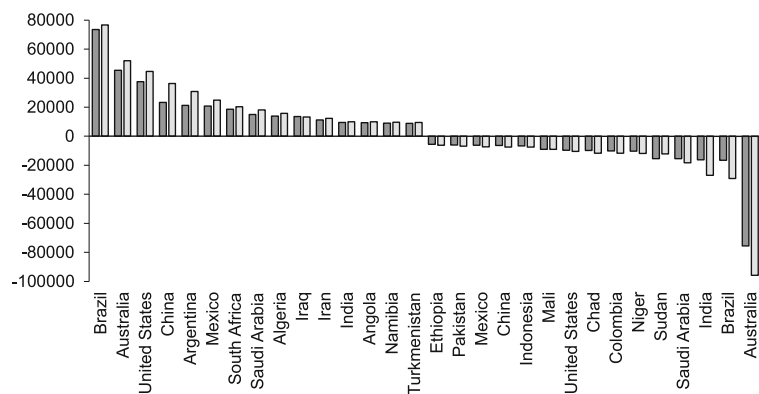
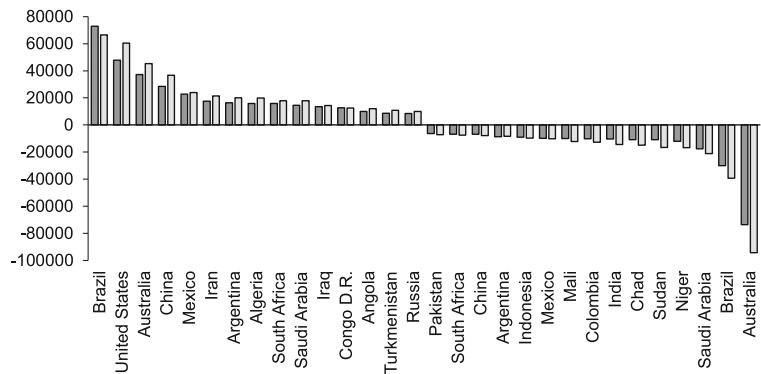


Fig. 6 Area (based on the number of cells) of habitat loss and gain in countries with the highest changes based on MIROC5 RCP 4.5 (dark) and RCP 8.5 (gray)



Although invasive *P. juliflora* has noticeably negative impacts on resident communities, attempts to eradicate invasive populations are inadequate. Recent documents highlight the urgent need to plan invasive species risk assessments to contribute to the development of management strategies and monitoring programs (McNeely 2001; Kettunen et al. 2009). Similar to other invading species, *P. juliflora* is highly vulnerable in early establishment stages when eradication efforts are more efficient and cost-effective. For example, Rejmánek (2000) outlined that 2 out of 3 management objectives for addressing alien invasive species including prevention and early detection are related to invasion prediction. SDMs represent a quick and cost-efficient tool to evaluate the current and future invasion potential of non-indigenous species (Guisan et al. 2013; Early and Sax 2014). In addition, SDMs facilitate the identification of areas with high susceptibility to invasion and help to prioritize management actions (Thuiller et al. 2005). According to our results monitoring plans and preventive measures should predominantly focus on the *P. juliflora*' northern ranges, particularly Mediterranean basin and North America, to prevent further spread and establishment of the species.

There are further drivers that could intensify the risk of invasive plants and change their distribution. Moreover, trends from human pressure and land use change, which is intensifying particularly in the Mediterranean Basin and Middle East (Maiorano et al. 2011; Early and Sax 2014), is an important issue for their native communities. In fact, land use degradation coupled with the introduction and plantation of invasive species through hampering the effective efficiency of the native species to track climate change increase the vulnerability of native communities (Gilman et al. 2010; Oliver and Morecroft 2014). Furthermore, fine-scale environmental

variables may affect distribution and abundance of *P. juliflora* (Wakie et al. 2014), a factor not considered in our models because of the focus on the climatic niche of the species and projection to the future. Detailed modeling using variables representing the fine-scale heterogeneity may provide more accurate results for local and regional land management. For example, remotely sensed indices such as normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), soil moisture, and topographic factors could be used to develop local or regional models of *P. juliflora* distribution.

Conclusion

Dispersal opportunities, ecological suitability, and naturalization in the new habitat facilitate the spread of the alien species in the new region (Rejmanek et al. 2005). Invasion possibilities can be predicted and evaluated before an invasion occurs (Thuiller et al. 2005). In response to changing climate, range shift takes place in the distribution of the species and might facilitate the invasion of the alien species to new areas. In this research, we used the concept of species distribution modeling and climatic variables to predict the current and future patterns of *P. juliflora*'s global distribution. Our results revealed that global warming favors *P. juliflora* and patterns of range expansion will be happening in the near future. The main strength of this research is to identify key geographical areas that are highly susceptible to invasions. Particularly, we found patterns of pollward expansion to higher latitudes, including North America, Mediterranean Basin, and Middle East, resulting in challenges for ecosystem management in these regions. Regarding the negative impacts

of *P. juliflora* on structure and function of the natural habitats in the invaded areas, findings of this study thus could be considered as a warning appliance for the environmental monitoring of the regions highly sensitive to the global invasion of the species.

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References

- Aboud, A. A., Kisoyan, P. K., & Coppock, D. L. (2005). Agropastoralists' wrath for the Prosopis tree: The case of the IL Chamus of Baringo District, Kenya. *Global Livestock Collaborative Research Support Program*. USA: University of California at Davis.
- Al-Rawahy, S. H., Al-Dhafri, K. S., & Al-Bahlany, S. S. (2003). Germination, growth and drought resistance of native and alien plant species of the genus *Prosopis* in the Sultanate of Oman. *Asian Journal of Plant Sciences*, 2(14), 1020–1023.
- Alban, L., Matorel, M., Romero, J., Grados, N., Cruz, G., & Felker, P. (2002). Cloning of elite, multipurpose trees of the *Prosopis juliflora/pallida* complex in Piura. *Peru Agroforestry Systems*, 54, 173–182.
- Alexander, J. M., & Edwards, P. J. (2010). Limits to the niche and range margins of alien species. *Oikos*, 119(9), 1377–1386.
- Broennimann, O., & Guisan, A. (2008). Predicting current and future biological invasions: both native and invaded ranges matter. *Biology Letters*, 4(5), 585–589.
- Chen, I.-C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid range shifts of species associated with high levels of climate warming. *Science*, 333(6045), 1024–1026.
- Davidson, A. M., Jennions, M., & Nicotra, A. B. (2011). Do invasive species show higher phenotypic plasticity than native species and, if so, is it adaptive? A meta-analysis. *Ecology Letters*, 14(4), 419–431.
- Early, R., & Sax, D. F. (2014). Climatic niche shifts between species' native and naturalized ranges raise concern for ecological forecasts during invasions and climate change. *Global Ecology and Biogeography*, 23(12), 1356–1365.
- Ehrenfeld, J. G. (2010). Ecosystem consequences of biological invasions. *Annual Review of Ecology, Evolution, and Systematics*, 41, 59–80.
- El-Keblawy, A., & Al-Rawai, A. (2005). Effects of salinity, temperature and light on germination of invasive *Prosopis juliflora* (Sw.) DC. *Journal of Arid Environments*, 61(4), 555–565.
- El-Keblawy, A., & Al-Rawai, A. (2007). Impacts of the invasive exotic *Prosopis juliflora* (Sw.) DC on the native flora and soils of the UAE. *Plant Ecology*, 190(1), 23–35.
- Elith, J., Graham, C. H., Anderson, R. P., Dudík, M., Ferrier, S., Guisan, A., et al. (2006). Novel methods improve prediction of species' distributions from occurrence data. *Ecography*, 29(2), 129–151.
- Elith, J., Kearney, M., & Phillips, S. (2010). The art of modelling range-shifting species. *Methods in Ecology and Evolution*, 1(4), 330–342.
- Evangelista, P. H., Kumar, S., Stohlgren, T. J., Jarnevich, C. S., Crall, A. W., Norman, J. B., III, et al. (2008). Modelling invasion for a habitat generalist and a specialist plant species. *Diversity and Distributions*, 14(5), 808–817.
- Fandohan, A. B., Oduor, A. M., Sodé, A. I., Wu, L., Cuni-Sanchez, A., Assédé, E., et al. (2015). Modeling vulnerability of protected areas to invasion by *Chromolaena odorata* under current and future climates. *Ecosystem Health and Sustainability*, 1(6), 1–12.
- Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W. J., et al. (2013). Evaluation of climate models. In *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Climate Change 2013* (Vol. 5, pp. 741–866).
- Franklin, J. (2010). *Mapping species distributions: Spatial inference and prediction*. Cambridge University Press.
- Franks, S. J., Weber, J. J., & Aitken, S. N. (2014). Evolutionary and plastic responses to climate change in terrestrial plant populations. *Evolutionary Applications*, 7(1), 123–139.
- Gallagher, R. V., Beaumont, L. J., Hughes, L., & Leishman, M. R. (2010). Evidence for climatic niche and biome shifts between native and novel ranges in plant species introduced to Australia. *Journal of Ecology*, 98(4), 790–799.
- Gallien, L., Douzet, R., Pratte, S., Zimmermann, N. E., & Thuiller, W. (2012). Invasive species distribution models—how violating the equilibrium assumption can create new insights. *Global Ecology and Biogeography*, 21(11), 1126–1136.
- Garcia, R. A., Cabeza, M., Rahbek, C., & Araújo, M. B. (2014). Multiple dimensions of climate change and their implications for biodiversity. *Science*, 344(6183), 1247579.
- Geesing, D., Al-Khawlani, M., & Abba, M. L. (2004). Management of introduced *Prosopis* species: can economic exploitation control an invasive species? *Unasylva, Forest threats*, 55, 36–44.
- Genovesi, P. (2005). Eradications of invasive alien species in Europe: a review. *Biological Invasions*, 7(1), 127–133.
- Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., Lawrence, D. M., Neale, R. B., Rasch, P. J., Vertenstein, M., Worley, P. H., Yang, Z. L., & Zhang, M. (2011). The community climate system model version 4. *Journal of Climate*, 24(19), 4973–4991.
- Gilman, S. E., Urban, M. C., Tewksbury, J., Gilchrist, G. W., & Holt, R. D. (2010). A framework for community interactions under climate change. *Trends in Ecology & Evolution*, 25(6), 325–331.
- Guisan, A., & Thuiller, W. (2005). Predicting species distribution: offering more than simple habitat models. *Ecology Letters*, 8(9), 993–1009.
- Guisan, A., Tingley, R., Baumgartner, J. B., Naujokaitis-Lewis, I., Sutcliffe, P. R., Tulloch, A. I., et al. (2013). Predicting species

- distributions for conservation decisions. *Ecology Letters*, 16(12), 1424–1435.
- Hellmann, J. J., Byers, J. E., Bierwagen, B. G., & Dukes, J. S. (2008). Five potential consequences of climate change for invasive species. *Conservation Biology*, 22(3), 534–543.
- Hijmans, R., Guarino, L., & Mathur, P. (2012). DIVA-GIS. Version 7.5. A geographic information system for the analysis of species distribution data. Available at: www.diva-gis.org.
- Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, 25(15), 1965–1978.
- Jama, B., & Zeila, A. (2005). Agroforestry in the drylands of eastern Africa: a call to action. *ICRAF Working Paper* Nairobi: World Agroforestry Centre.
- Jeschke, J. M., Bacher, S., Blackburn, T. M., Dick, J. T., Essl, F., Evans, T., et al. (2014). Defining the impact of non-native species. *Conservation Biology*, 28(5), 1188–1194.
- Kettunen, M., Genovesi, P., Gollasch, S., Pagad, S., Starfinger, U., ten Brink, P., et al. (2009). Technical support to EU strategy on invasive alien species (IAS). *Institute for European Environmental Policy (IEEP)*, Brussels, 44.
- Kramer-Schadt, S., Niedballa, J., Pilgrim, J. D., Schröder, B., Lindenbom, J., Reinfelder, V., Stillfried, M., Heckmann, I., Scharf, A. K., Augeri, D. M., Cheyne, S. M., Hearn, A. J., Ross, J., Macdonald, D. W., Mathai, J., Eaton, J., Marshall, A. J., Semiadi, G., Rustam, R., Bernard, H., Alfred, R., Samejima, H., Duckworth, J. W., Breitenmoser-Wuersten, C., Belant, J. L., Hofer, H., & Wilting, A. (2013). The importance of correcting for sampling bias in MaxEnt species distribution models. *Diversity and Distributions*, 19(11), 1366–1379. <https://doi.org/10.1111/ddi.12096>.
- Kumar, S., Neven, L. G., Zhu, H., & Zhang, R. (2015). Assessing the global risk of establishment of *Cydia pomonella* (Lepidoptera: Tortricidae) using CLIMEX and MaxEnt niche models. *Journal of Economic Entomology*, 108(4), 1708–1719.
- Liu, C., Berry, P. M., Dawson, T. P., & Pearson, R. G. (2005). Selecting thresholds of occurrence in the prediction of species distributions. *Ecography*, 28(3), 385–393.
- Maiorano, L., Falcucci, A., Zimmermann, N. E., Psomas, A., Pottier, J., Baisero, D., Rondinini, C., Guisan, A., & Boitani, L. (2011). The future of terrestrial mammals in the Mediterranean basin under climate change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366(1578), 2681–2692.
- McCary, M. A., Mores, R., Farfan, M. A., & Wise, D. H. (2016). Invasive plants have different effects on trophic structure of green and brown food webs in terrestrial ecosystems: a meta-analysis. *Ecology Letters*, 19(3), 328–335.
- McNeely, J. A. (2001). Global strategy on invasive alien species: IUCN.
- Mwangi, E., & Swallow, B. (2008). *Prosopis juliflora* invasion and rural livelihoods in the Lake Baringo area of Kenya. *Conservation and Society*, 6(2), 130–140.
- Oliver, T. H., & Morecroft, M. D. (2014). Interactions between climate change and land use change on biodiversity: attribution problems, risks, and opportunities. *Wiley Interdisciplinary Reviews: Climate Change*, 5(3), 317–335.
- Parmesan, C. (2006). Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics*, 37, 637–669.
- Pasiecznik, N. M., Harris, P. J. C., & Smith, S. J. (2004). *Identifying tropical *prosopis* species: a field guide*. Coventry, UK: International Research Department, HDRA.
- Pejchar, L., & Mooney, H. A. (2009). Invasive species, ecosystem services and human well-being. *Trends in Ecology & Evolution*, 24(9), 497–504.
- Pereira, H. M., Leadley, P. W., Proença, V., Alkemade, R., Scharlemann, J. P., Fernandez-Manjarrés, J. F., et al. (2010). Scenarios for global biodiversity in the 21st century. *Science*, 1196624.
- Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, 190(3–4), 231–259.
- Pyšek, P., Sádlo, J., Mandák, B., & Jarošík, V. (2003). Czech alien flora and the historical pattern of its formation: what came first to Central Europe? *Oecologia*, 135(1), 122–130.
- Qian, H., & Ricklefs, R. E. (2006). The role of exotic species in homogenizing the North American flora. *Ecology Letters*, 9(12), 1293–1298.
- Rejmánek, M. (2000). Invasive plants: approaches and predictions. *Austral Ecology*, 25, 497–506.
- Rejmánek, M., & Richardson, D. M. (1996). What attributes make some plant species more invasive? *Ecology*, 77(6), 1655–1661.
- Rejmanek, M., Richardson, D. M., Higgins, S. I., Pitcairn, M. J., & Grotkopp, E. (2005). Ecology of invasive plants: state of the art. In H. A. Mooney, R. Mack, J. A. McNeely, L. E. Neville, P. J. Schei, & J. K. Waage (Eds.), *Invasive alien species: a new synthesis* (pp. 104–161): Island Press, Washington, DC.
- Scheffers, B. R., De Meester, L., Bridge, T. C., Hoffmann, A. A., Pandolfi, J. M., Corlett, R. T., et al. (2016). The broad footprint of climate change from genes to biomes to people. *Science*, 354(6313), aaf7671.
- Schirmel, J., Bundschuh, M., Entling, M. H., Kowarik, I., & Buchholz, S. (2016). Impacts of invasive plants on resident animals across ecosystems, taxa, and feeding types: a global assessment. *Global Change Biology*, 22(2), 594–603.
- Scott, J., & Panetta, F. (1993). Predicting the Australian weed status of southern African plants. *Journal of Biogeography*, 20, 87–93.
- Shabani, F., & Kumar, L. (2015). Should species distribution models use only native or exotic records of existence or both? *Ecological Informatics*, 29, 57–65.
- Shabani, F., Kumar, L., & Ahmadi, M. (2016). A comparison of absolute performance of different correlative and mechanistic species distribution models in an independent area. *Ecology and Evolution*, 6(16), 5973–5986.
- Sharma, R., & Dakshini, K. (1998). Integration of plant and soil characteristics and the ecological success of two shape *Prosopis* species. *Plant Ecology*, 139(1), 63–69.
- Shiferaw, H., Teketay, D., Nemomissa, S., & Assefa, F. (2004). Some biological characteristics that foster the invasion of *Prosopis juliflora* (Sw.) DC. At middle awash Rift Valley area, North-Eastern Ethiopia. *Journal of Arid Environments*, 58(2), 135–154.
- Thuiller, W., Richardson, D. M., PYŠEK, P., Midgley, G. F., Hughes, G. O., & Rouget, M. (2005). Niche-based modelling

- as a tool for predicting the risk of alien plant invasions at a global scale. *Global Change Biology*, *11*(12), 2234–2250.
- Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al. (2011). The representative concentration pathways: an overview. *Climatic Change*, *109*(1–2), 5–31.
- VanDerWal, J., Murphy, H. T., Kutt, A. S., Perkins, G. C., Bateman, B. L., Perry, J. J., & Reside, A. E. (2013). Focus on poleward shifts in species' distribution underestimates the fingerprint of climate change. *Nature Climate Change*, *3*(3), 239–243.
- Vilà, M., Espinar, J. L., Hejda, M., Hulme, P. E., Jarošík, V., Maron, J. L., Pergl, J., Schaffner, U., Sun, Y., & Pyšek, P. (2011). Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. *Ecology Letters*, *14*(7), 702–708.
- Wakie, T. T., Evangelista, P. H., Jarnevich, C. S., & Laituri, M. (2014). Mapping current and potential distribution of non-native *Prosopis juliflora* in the Afar region of Ethiopia. *PLoS One*, *9*(11), e112854.
- Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J., et al. (2002). Ecological responses to recent climate change. *Nature*, *416*(6879), 389–395.
- Wang, W., Tang, X., Zhu, Q., Pan, K., Hu, Q., He, M., & Li, J. (2014). Predicting the impacts of climate change on the potential distribution of major native non-food bioenergy plants in China. *PLoS One*, *9*(11), e111587.
- Warren, D. L., Glor, R. E., & Turelli, M. (2010). ENMTools: a toolbox for comparative studies of environmental niche models. *Ecography*, *33*(3), 607–611.
- Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., Chikira, M., Ogura, T., Sekiguchi, M., Takata, K., Yamazaki, D., Yokohata, T., Nozawa, T., Hasumi, H., Tatebe, H., & Kimoto, M. (2010). Improved climate simulation by MIROC5: mean states, variability, and climate sensitivity. *Journal of Climate*, *23*(23), 6312–6335.
- Wiens, J. J., Ackerly, D. D., Allen, A. P., Anacker, B. L., Buckley, L. B., Cornell, H. V., Damschen, E. I., Jonathan Davies, T., Grytnes, J. A., Harrison, S. P., Hawkins, B. A., Holt, R. D., McCain, C. M., & Stephens, P. R. (2010). Niche conservatism as an emerging principle in ecology and conservation biology. *Ecology Letters*, *13*(10), 1310–1324.
- Wisz, M. S., Hijmans, R., Li, J., Peterson, A. T., Graham, C., Guisan, A., et al. (2008). Effects of sample size on the performance of species distribution models. *Diversity and Distributions*, *14*(5), 763–773.
- Yousefi, M., Ahmadi, M., Nourani, E., Behrooz, R., Rajabizadeh, M., Geniez, P., & Kaboli, M. (2015). Upward altitudinal shifts in habitat suitability of mountain vipers since the last glacial maximum. *PLoS One*, *10*(9), e0138087.
- Zavaleta, E. S., Hobbs, R. J., & Mooney, H. A. (2001). Viewing invasive species removal in a whole-ecosystem context. *Trends in Ecology & Evolution*, *16*(8), 454–459.

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