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Predicting future distribution patterns of *Jatropha* gossypiifolia L. in South Africa in response to climate change

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A B S T R A C T

Invasive alien species such as Bellyache bush (*Jatropha gossypiifolia* L.) pose immense threats to global food security, biodiversity, ecosystem integrity and provision of ecosystem services. The Bellyache bush has generally been naturalised in Africa but poses vast management challenges in the African Savannah, yet there is little knowledge of its spatial distribution and future potential invasion risk.

In this study, we modelled the spatial distribution of Bellyache bush in South Africa as a function of key biophysical factors using maximum entropy (MaxEnt) and estimated its potential invasion risk into native environments because of climate change.

Results show that temperature seasonality, mean annual temperature range and mean temperature of the coldest month are the key factors explaining Bellyache bush distribution in South Africa.

The response of the occurrence of Bellyache bush to the temperature variables demonstrated that the suitable habitat for Bellyache bush ranged between 10° and 30 °C while the tolerance to precipitation range is very wide (400 mm – > 2500 mm/year^{-1}). The total area suitable for Bellyache bush propagation in South Africa is ~129 034 km^2 (10% of the total land area of South Africa) in the current and will increase because of climate change to ~510 914 km^2 (40% of the total land area of South Africa).

Our results suggest that we can estimate the spatial distribution and Bellyache bush invasion risk areas in South Africa. This implies that policies and management strategies for further Bellyache bush invasions in South Africa can now informatively be targeted to high priority areas.

1. Introduction

There is a growing global critical concern regarding biological invasions caused by the changing climate and its variability (Hulme, 2009). The Millennium Ecosystem Assessment considers the invasive alien species (IAS) as the second most important global threat to biological diversity (Millennium Ecosystem Assessment, 2005). On the other hand, the convention on biological diversity (CBD) also regards IAS as a global challenge because of their numerous severe negative impacts on food security, human health, economic development and biodiversity (Convention on Biological Diversity, 2016; Moshobane et al., 2017; Shivambu et al. 2020). The United Nations sustainable development goals (UNSDGs), goal number 15, aims to protect, restore and combat desertification and biodiversity loss. In particular, the Aichi biodiversity target number 9 states that, by 2020, IAS and pathways should have been identified and prioritized, priority species controlled or eradicated, and measures are put in place to manage pathways to prevent their introduction and establishment (Convention on Biological Diversity, 2016).

Given the numerous and complex pathways for IAS introductions and that multiple alien species are already present in many countries (Hulme, 2009), the number continue to increase (Moshobane et al., 2020a), it is very vital to prioritise control and eradication efforts on those species and pathways which are resource-effective and will have the greatest positive impact on biodiversity (Convention on Biological Diversity, 2016; Keane and Crawley 2002). Obtaining reliable estimates of the cost of eradication of IAS is challenging, but often, costs go beyond billions of US$ relative to the occupied area and the clearing methods employed (Jardine and Sanchirico 2018). Currently,

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the key concern amongst the scientific and policymaking communities, is that the IAS population dispersions are likely to change beyond the current known species distribution ranges thereby overstretching the existing control mechanisms and budgets for the control of invasive species such as the Bellyache bush (*Jatropha gossypiifolia.* Linnaeus 1753: Caminade et al., 2012; Jardine and Sanchirico, 2018).

The Bellyache bush is a flowering plant belonging to the genus Jatropha and the family *Euphorbiaceae*. The key importance of the species belonging to the Jatropha genus are their medicinal traits which have been realised in many countries including Pakistan, Brazil, India and many African countries (Félix-Silva et al., 2014). However, the Bellyache bush is potentially an invasive shrub in most African, Asian and Australian continents, with its native origin, traced back to Mexico, South America, Gujarat State and the Caribbean islands (Wu et al., 2019). Bellyache bush was introduced to many parts of the world, primarily for medicinal or garden ornamental purposes (Prentis et al., 2009). In all its introduced range, it invades disturbed habitats along with roadside areas and forest openings, thereby competitively excluding the native vegetation plant species diversity through preventing regeneration of native shrubs and trees (Roberts and Florentine, 2021), particularly in the absence of fire as a natural controlling mechanism (Bebawi & Campbell, 2002b, 2002a).

In Australia, the Bellyache bush is listed as a priority environmental weed in five Natural Resource Management regions and is considered amongst the top 200 most invasive plant species with high toxicity to both humans and animals (Parsons and Cuthbertson, 2001). However, in South Africa, the species is not yet registered on the list for alien and invasive species (A&IS) as outlined in the South African national environmental management biodiversity act (Department of Environmental Affairs, 2004; Moshobane et al., 2019). Currently, the species is placed on the species under surveillance for possible eradication or containment targets (SUSPECT) list, making its empirical distribution and risk assessment urgent. In this current study, we assert that an understanding of the distribution of Bellyache bush is paramount for the development of informed strategies and recommendations for regulations or listing of the species based on observed evidence of risks associated with the invasion prowess of the species, particularly considering the pending climate change (Moshobane et al., 2019). The level to which an IAS can effectively be managed depends on the understanding of its present population and the key determinants of its distribution (Convention on Biological Diversity, 2016; Moyo et al., 2019).

Therefore, to improve our understanding of the distribution of Bellyache bush and its associated risks on biodiversity, we aimed to predict its potential distribution and invasion risk under the current and future climatic scenarios in South Africa using established species distribution modelling (SDM) approaches i.e., maximum entropy (MaxEnt). MaxEnt models correlate the present location (presence-only data) of a species with the appropriate predictor variables (e.g., bioclimatic variables), thereby providing a statistical link between the spatial differences of the predictor variables and the spatial dispersion of the species within the environment, in our case Bellyache bush (Ayebare et al., 2018). However, the accuracy and reliability of these SDMs rely on the precision and distribution of the 'presence-only' data used, tied with a careful selection of the most relevant bioclimatic predictor variables (Elith et al., 2010a; Mudereri et al., 2019). Several studies have also used SDMs and machine learning to establish the distribution of similar invasive species in South Africa (Mkunyana et al., 2018; Moshobane et al., 2020b; Mtengwana et al., 2021; Thamaga and Dube, 2019)

There is a huge gap in information regarding the use of such technology on analysis and mapping of Bellyache bush distribution and risk, particularly the influence of climate change on the distribution of Bellyache bush in South Africa (Moshobane et al., 2017). Additionally, many studies have investigated the effects of climate change on a range of species, showing that change in climatic conditions has a profound impact on species distribution ranges (Ayebare et al., 2018; Masocha and Dube, 2017). The risks inflicted by these IAS i.e., Bellyache bush are likely to be worsened by climate change and the inadequate adaptive or mitigation capacity, in addition to the limited impact documentation leading to inadequate preparedness (Niang et al., 2014). Thus, identifying and controlling the Bellyache bush species, before they spread to new environments, requires better surveillance and constant monitoring with adequate, cost-effective tools and methods, such as presented in this current study.

2. Methodology

2.1. Study area

Predictions of the occurrence of Bellyache bush were conducted in the whole country of South Africa using global occurrence data (Fig. 1). The climate of South Africa is varied but generally characterized by high humidity and heavy rainfall. It is characterised by a subtropical and savanna climate, with warm summers and mild winters with daily temperatures ranging between 25 and 40 °C in summer and between 22 and 26 °C in winter (Fig. 1). Rainfall is highly seasonal with 95% occurring between October and March. The average rainfall is about 800 mm, but it often varies spatially and temporarily.

2.2. Reference occurrence data

We gathered and used global occurrence reference points from the Global Biodiversity Information Facility (GBIF, 2019). Both local and global 'presence-only' samples were verified on Google Earth® for positional accuracy. A total of 2270 samples obtained from GBIF were subjected to duplication correction, positional accuracy, and spatial filtering in a geographical information system (GIS), using a standard distance of 20 km between the adjacent points to reduce spatial autocorrelation and potential sampling bias (Kramer-Schadt et al., 2013). The points data were examined to eliminate redundant and overlapping samples (Araújo et al., 2019). We retained a total of 1550 presence points that were representative of the entire world distribution range of the Bellyache bush. Thus, these points were enough for use in MaxEnt to predict and project the occurrence of the species to a new environment and temporal space (Zurell et al., 2012; Mesgaran et al., 2014). The occurrence points were arranged and formatted for input in the MaxEnt model.

2.3. Bioclimatic variables

The global bioclimatic data used for our analysis (current and future bioclimatic variables) were downloaded at ~1 km x 1 km pixel size from WorldClim (www.worldclim.org). We used the global, 19 bioclimatic variables to determine the key climatic covariates influencing and controlling the distribution of Bellyache bush in South Africa. In predicting future climate scenarios, four representative concentration pathways (RCPs) have been set by the intergovernmental panel on climate change (IPCC) using the total radio-active forcing of values 2.6, 4.5, 6 and 8.5 watt/m2 (IPCC, 2014). We compared the current climate data (1950–2000) and one-time step into the future using the highest predicted carbon concentration i.e. RCP8.5 for carbon dioxide concentrations predicted for 2050 (average of predictions for 2041–2060) in our analysis (Abdelaal et al., 2019). The future climatic data were obtained from the fourth version of the community climate system model (CCSM4), which is one of the models that provide the most efficient global future climate projections (Mohammadi et al., 2019).

A multi-collinearity test on the 19 bioclimatic variables to reduce redundancy and overfitting of the model brought by highly correlated variables was preliminarily performed on all the variables. The Pearson

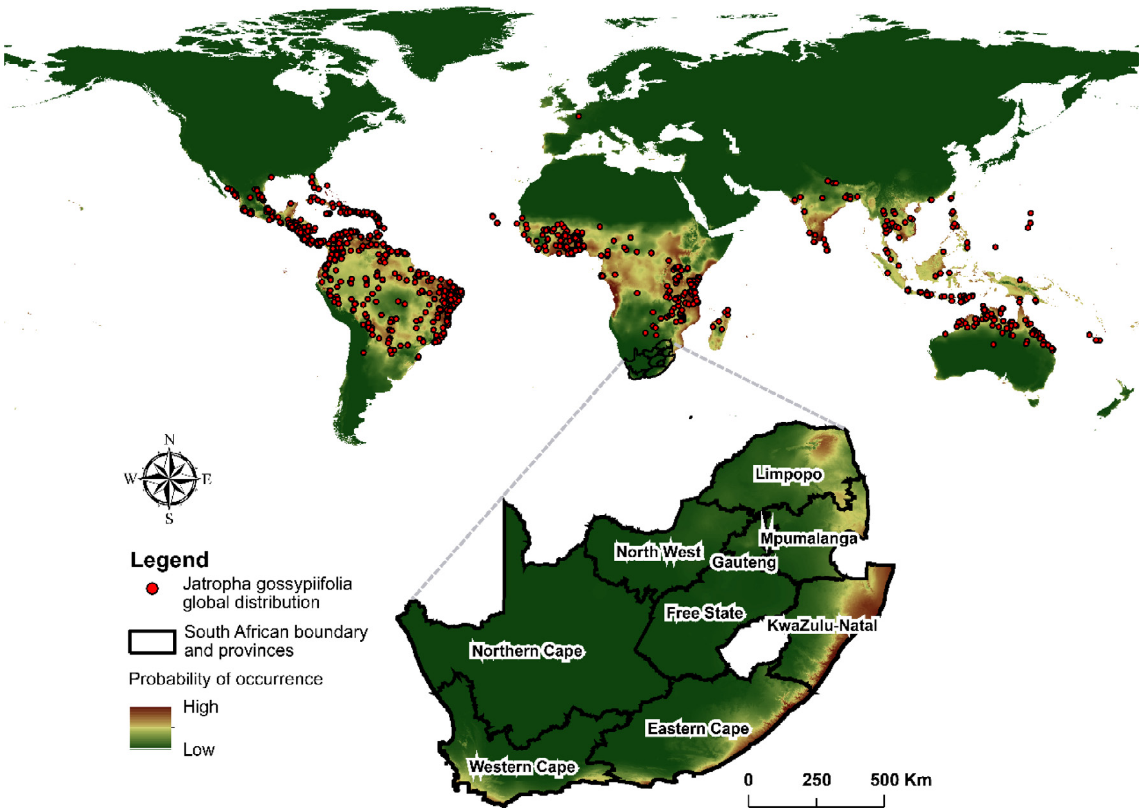

Fig. 1. The relative location of South Africa and its administrative provinces. The red dots show the global location of *Jatropha gossypiifolia* in all the continents.

correlation coefficient ($r \geq 0.85$) and the overall percentage contribution of the variables derived from MaxEnt were used to reduce the multi-collinearity amongst the predictors (Merow et al., 2013). In cases where two predictors were correlated, only ecologically viable predictors were retained (Muposhi et al., 2016). This reduction of predictor variables resulted in only 6 out of the 19 bioclimatic variables for modelling, which are highlighted in bold in Table 1. These selected variables include temperature seasonality (Bio4), minimum temperature of the coldest month (Bio6), temperature annual range (Bio7), annual precipitation (Bio12), precipitation of the wettest month (Bio13) and precipitation of wettest quarter (Bio16).

2.4. MaxEnt model implementation and accuracy evaluation

In this study, we used the MaxEnt algorithm (version 3.4.1) (Phillips et al., 2006). MaxEnt has been widely employed to predict species distribution because of its statistical robustness procedures, adaptability to various environments, sample sizes and its high performance across several niche modelling methods for 'presence-only' data (Masocha and Dube, 2017; Marchioro and Krechemer, 2018; Mudereri et al., 2020). The "ENMevaluate" function in the package "ENMeval" (Muscarella et al., 2014) available in R-software (R Core Team, 2019) was used to derive optimum tuning and parameter

Table 1
Bioclimatic variables used in the MaxEnt models for *Jatropha gossypiifolia* L. suitable habitat prediction together with their variable and permutation importance. The variables in bold were used in the final prediction after eliminating the correlated variables, their corresponding unit of measurement and percentage contribution to the model.

BioClim Code	Bioclimatic variable	Variable importance (%)	Permutation importance
Bio1	Annual Mean Temperature	0.6	0
Bio2	Mean Diurnal Range [Mean of monthly (max temp−min temp)]	6.9	8.3
Bio3	Iso-thermality (Bio2/Bio7) (× 100)	0.2	1.9
Bio4	**Temperature Seasonality (standard deviation × 100)**	**41.7**	**1.8**
Bio5	Maximum Temperature of Warmest Month	0.6	0
Bio6	**Min Temperature of Coldest Month**	**1.5**	**33.1**
Bio7	**Temperature Annual Range (Bio5−Bio6)**	**1.2**	**9.8**
Bio8	Mean Temperature of Wettest Quarter	0.7	1.9
Bio9	Mean Temperature of Driest Quarter	0.7	0.5
Bio10	Mean Temperature of Warmest Quarter	1.1	3.6
Bio11	Mean Temperature of Coldest Quarter	1.8	1.3
Bio12	**Annual Precipitation**	**4.9**	**9.6**
Bio13	**Precipitation of Wettest Month**	**4.6**	**0**
Bio14	Precipitation of Driest Month	0.2	0.1
Bio15	Precipitation Seasonality (Coefficient of Variation)	1.1	2.2
Bio16	**Precipitation of Wettest Quarter**	**3.8**	**2.6**
Bio17	Precipitation of Driest Quarter	0.6	0
Bio18	Precipitation of Warmest Quarter	0.4	1.6
Bio19	Precipitation of Coldest Quarter	1.3	1.5

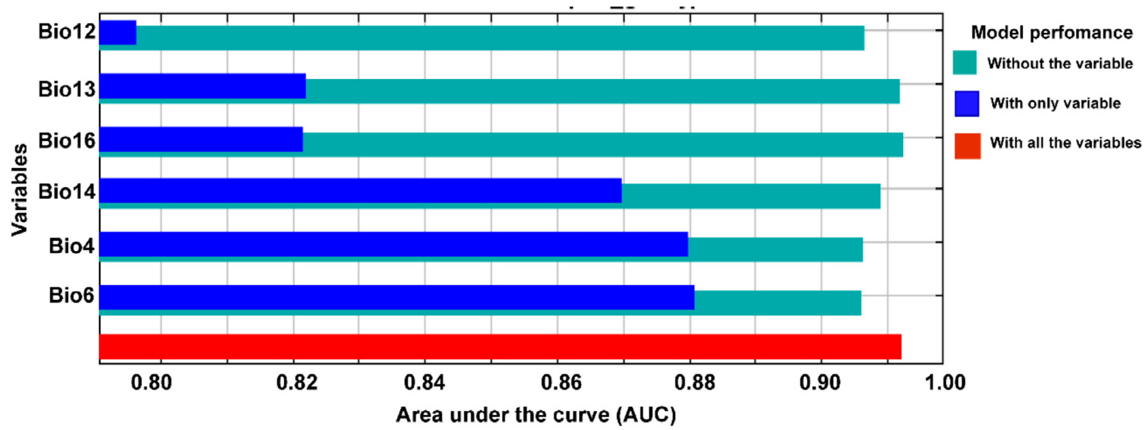

Fig. 2. Relative contribution and importance of the environmental variables used in the MaxEnt modelling of *Jatropha gossypiifolia* L. habitat suitability in South Africa as measured by contribution towards the area under the curve (AUC) derived from the Jackknife analysis in MaxEnt.

settings for the MaxEnt models. This approach calculates multiple metrics to aid in selecting optimum model settings that balance goodness-of-fit and model complexity (Muscarella et al., 2014). The following model parameters derived from “ENMeval” were applied in the MaxEnt models to perform the Bellyache bush habitat suitability modelling in South Africa: i.e., linear/quadratic/product: 0.05, categorical: 0.250, threshold: 1.00, hinge: 0.500, multivariate environmental similarity surface (MESS) analysis, clamping, extrapolate and fade with clamping.

The MESS analysis in MaxEnt quantifies the measure of projection uncertainty by calculating the similarity of each point in the projected region to a set of reference points (Mesgaran et al., 2014). Furthermore, using the above-mentioned setting parameters, we projected the potential current and future Bellyache bush occurrence using the global occurrence ‘presence-only’ data to predict the localised distribution in South Africa (Elith et al., 2010b; Zurell et al., 2012). We replicated our model 10 times and used the average of the 10 probability outputs to determine the optimum habitat suitability and performance of the models. The data was split into 50% (n = 775) of the occurrence points for training while 50% (n = 775) were retained for testing the model (Mudereri et al., 2020). The comparative relevance of each environmental predictor for the models of Bellyache bush was evaluated using the overall percentage contribution, permutation importance of each variable and area under the curve (AUC) of the Jackknife test, which are all available in MaxEnt (Merow et al., 2013).

The prediction precision was validated using the AUC of the receiver operating characteristic (ROC). The sensitivity (true positives) was plotted against specificity (false positives) to generate AUC. The values of AUC range between 0 and 1. AUC values closer to 1, suggest a perfect performance of the model whereas an AUC value of 0.50 indicates that the model did not perform better than random (Allouche et al., 2006). Herein, we report the AUC of the current climate scenario, since there are no future occurrence points to validate our future predictions. However, it is assumed that if the model performs well with the currently available data, it will replicate the same strength when used to project predictions into the future (Chemura et al., 2021).

The chief graphic outputs of the MaxEnt application includes maps, highlighting the habitat suitability of Bellyache bush, with values ranging from 0 (unsuitable) to 1 (optimum). We reclassified the suitable area into two classes namely relatively unsuitable (0–0.3) and potentially suitable (0.31–1). The selection of these breaks was intuitively based on the probability distribution of the prediction and also following Abdelaal et al. (2019). The two classes were necessary to calculate the total area of potential suitability in South Africa. Further, an “image differencing” approach was conducted in a GIS between the current and future prediction images to derive the suitability changes i.e., Bellyache bush suitability gain or loss.

2.5. Statistical analysis

Using the predicted outputs, we generated 100 random points in a GIS environment that were used to evaluate the correlation between the current and future climate scenarios. For each of these random points, the occurrence data for South Africa was extracted to coordinate specific probabilities of occurrence in the current and future predicted scenarios. Using these extracted values, we statistically tested for correlation and significant differences in the probability of occurrence between the current and future climate scenarios using the Pearson correlation coefficient (r^2) and a pairwise student t-test. These statistics were both calculated in R-software using the “agricolae” package (Mendiburu, 2019)

3. Results

3.1. MaxEnt models evaluation

Both MaxEnt models for the prediction and projection of the Bellyache bush potential habitat using the current and future (RCP8.5: 2050) provided satisfactory AUC results greater than 0.9 using both the test and training datasets of the replicated models. These results demonstrate that our models provided a very good predictive performance of the occurrence of Bellyache bush in South Africa.

Temperature based variables were the most relevant predictors compared to precipitation (Fig. 2). Bio4 had the highest contribution to the model training (Table 2) whilst Bio6 had the highest permutation importance as pointed by all the measures used in our analysis

Table 2
Variable importance measured by the percentage contribution to the model and the permutation importance derived from the MaxEnt modelling of *Jatropha gossypiifolia* L. habitat suitability in South Africa.

Bioclimatic variable	Percentage contribution	Permutation importance
Bio4	55.4	3.6
Bio6	21.6	59.4
Bio7	7.1	22.2
Bio13	6.8	0.3
Bio12	6.4	8.4
Bio16	2.8	6.1

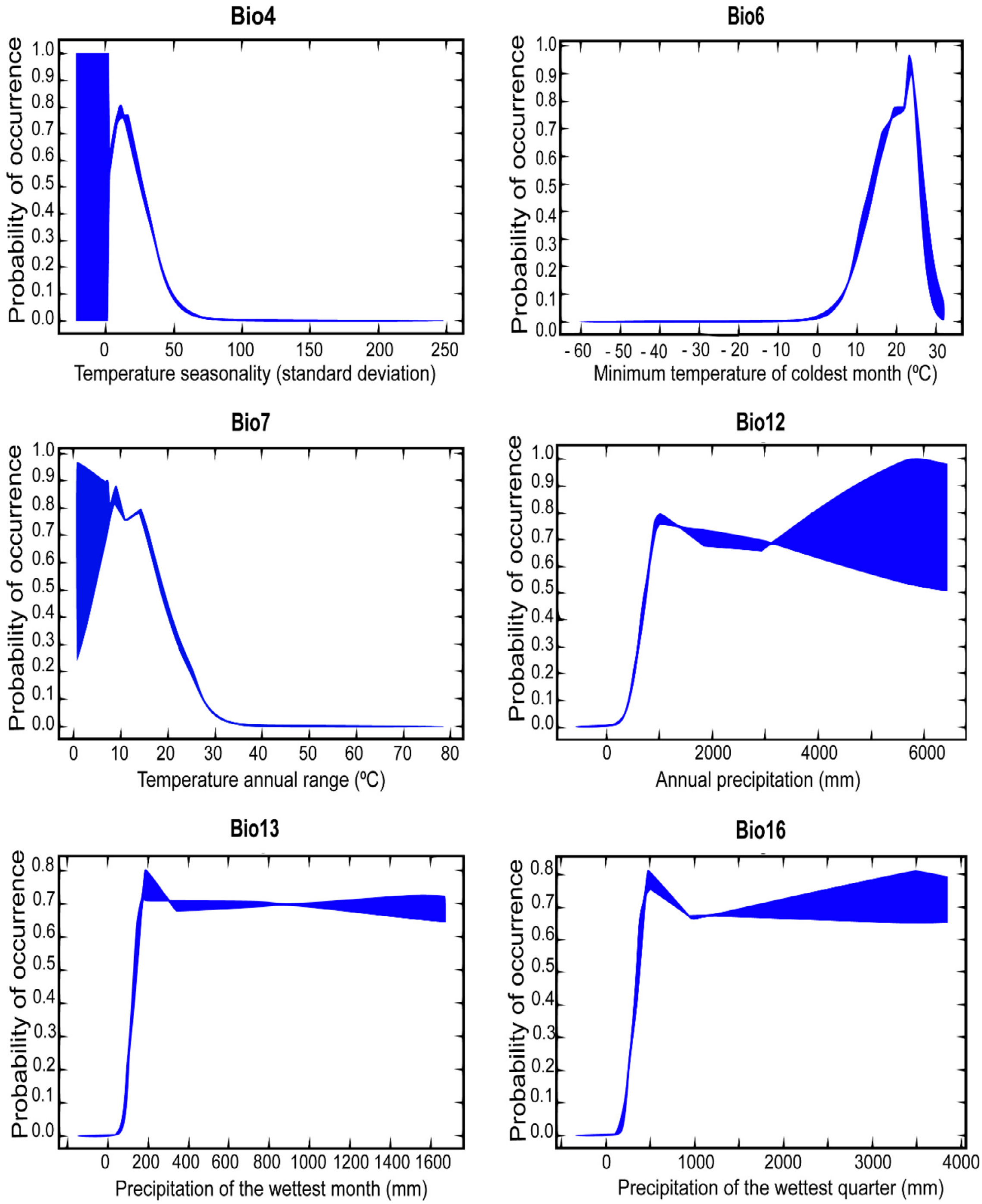

Fig. 3. Response curves derived from MaxEnt Models showing the influence of the six bioclimatic variables (Bio4; Bio6; Bio7; Bio12; Bio13; and Bio16) on the probability of occurrence of *Jatropha gossypiifolia* L. in South Africa.

(i.e. Jackknife AUC, overall percentage contribution and permutation importance). Based on the Jackknife results, Bio7 recorded the highest gain when used in isolation, therefore, appears to provide the most useful information individually. Similarly, Bio13 contributed the most amongst the precipitation variables but had relatively lower permutation importance (0.3) compared to Bio12 (8.4).

3.2. Individual bioclimatic variable responses to the prediction of J. gossypiifolia L. occurrence

The response of the occurrence of the Bellyache bush to the temperature variables i.e. Bio4; Bio6 and Bio7 demonstrated that its suitable habitat ranged between 10° and 30 °C. Furthermore, Bellyache bush was predicted within very high precipitation regions with rainfall ranges between ~ 400 mm and 2500 mm/year (Fig. 3) and still performed very well in very high rainfall intensity areas (>3000 mm).

3.3. Habitat suitability under current and future climate conditions

Our results show that the Bellyache bush invasion risk and current potential distribution varied in the different sites but is mainly spread along the coastal areas in the northern and eastern regions of the country (Fig. 4). These regions occur in 5 of the nine provinces of the

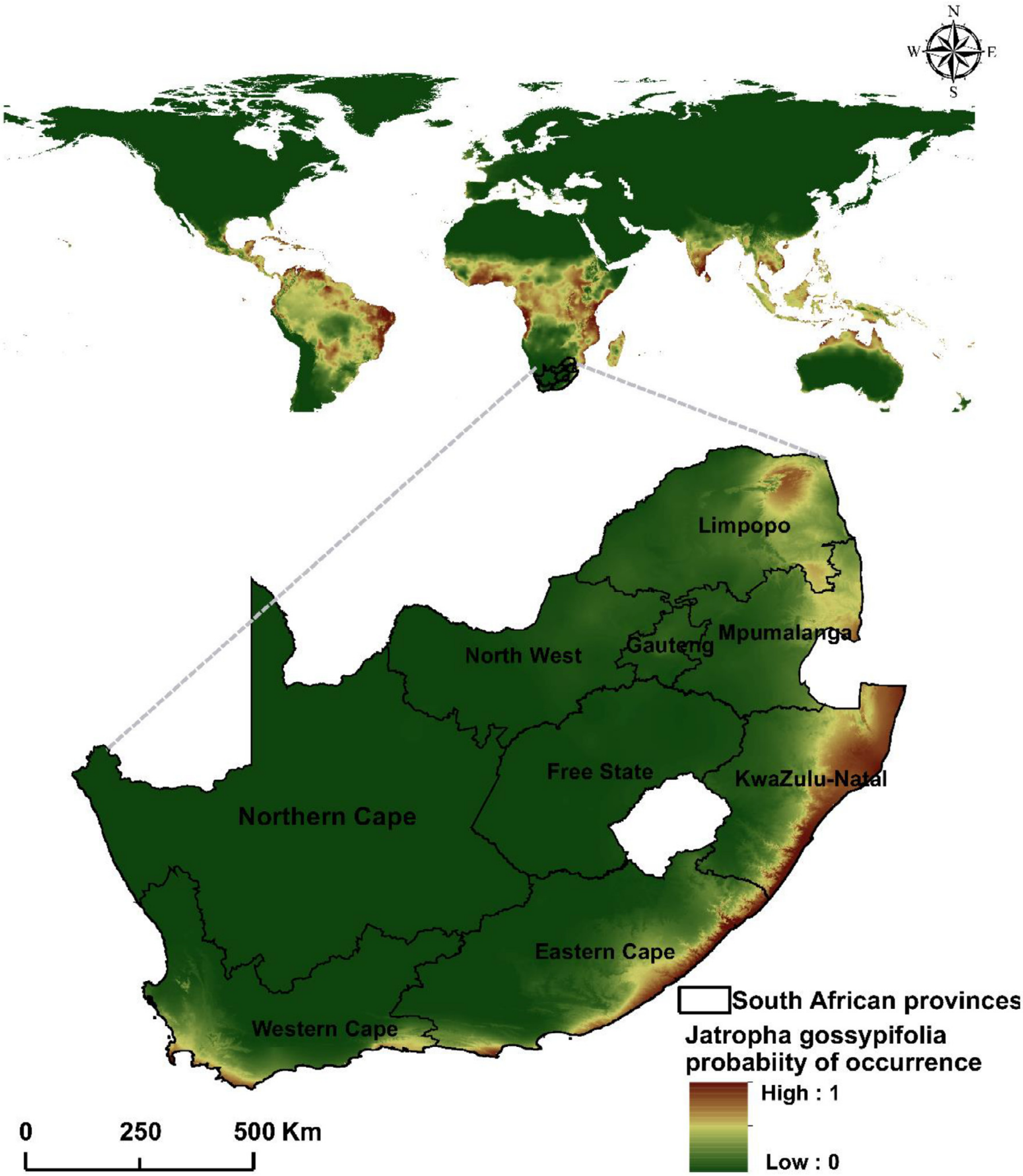

Fig. 4. Current potential distribution of Bellyache bush (*Jatropha gossypiifolia* L.) in South Africa. The green colour shows the area of low occurrence risk while the warmer colours show a moderate to a high probability of occurrence.

country. The provinces that potentially host Bellyache bush are Limpopo, Mpumalanga, KwaZulu natal, Eastern Cape and Western Cape. However, our results show a very high increase in the area coverage, which has the potential to be invaded by the Bellyache bush in the future because of climate change. Accordingly, the risk of the Bellyache bush invasion will likely spread to all the provinces in South Africa except for the Northern Cape. Additionally, the intensity of the invasion will be high compared to the current climate regime with the entire KwaZulu natal province highly susceptible to Bellyache bush invasion than other provinces (Fig. 5). The total area suitable for Bellyache bush propagation in South Africa is ~129 034 km^2 which covers ~10% of the total land area of South Africa in the current and will increase because of climate change to ~510 914 km^2 (~40% of the total land area of South Africa).

3.4. Distribution of the Bellyache bush potential area suitability gain

Fig. 6 shows the analysis of the areas that were previously not susceptible to invasion risk but are likely to be at the 'highest' potential of invasion risk in the face of climate change. These areas are within the five provinces that currently hosts the Bellyache bush namely: Limpopo, Mpumalanga, KwaZulu natal, Eastern Cape and Western Cape.

3.5. Statistical analysis

There was a relatively low correlation (r^2 =0.58) between the current and future potential distribution of Bellyache bush in South Africa. This was confirmed by the *t*-test which showed that the

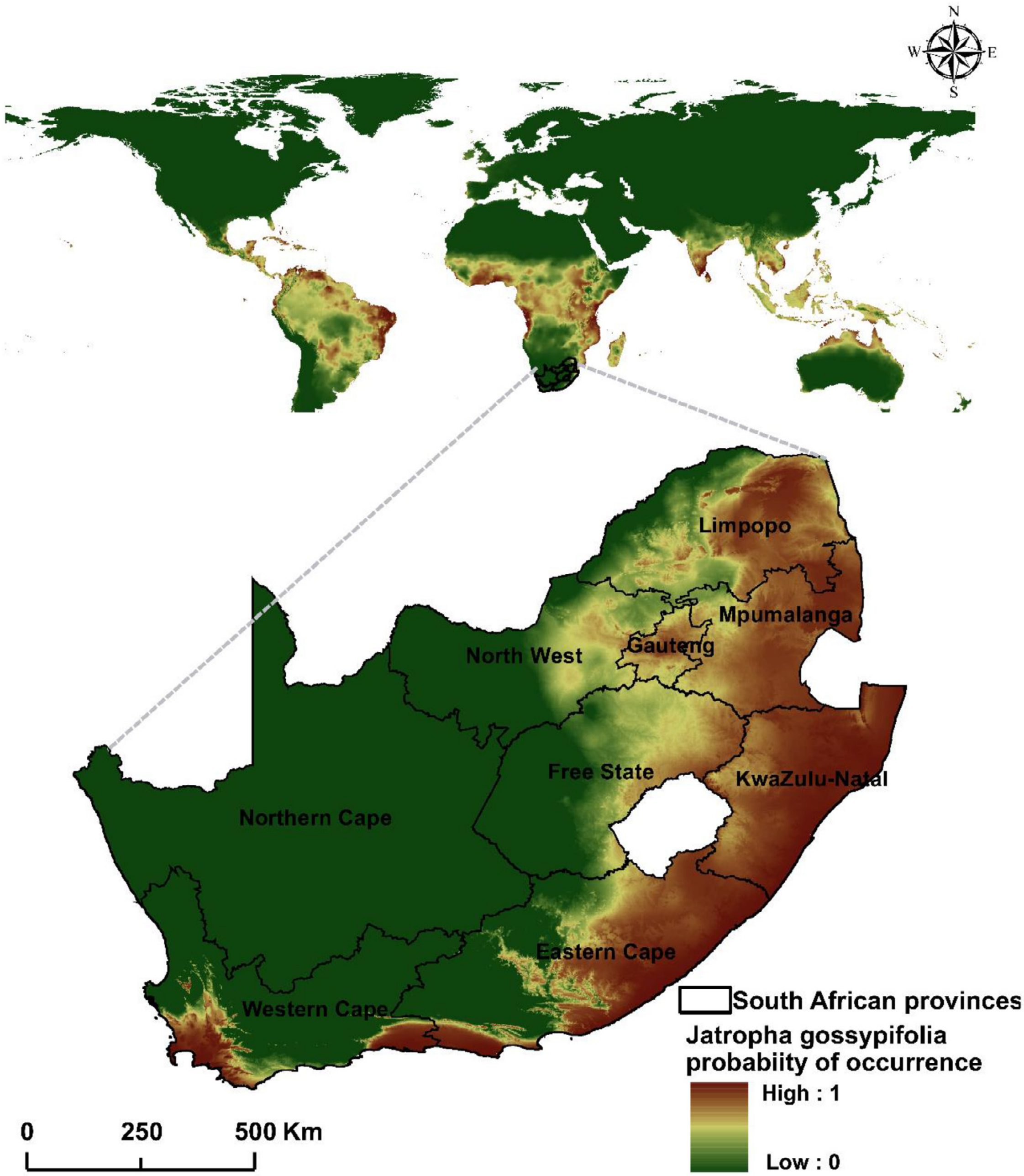

Fig. 5. Potential future distribution of Bellyache bush (*Jatropha gossypiifolia* L.) in South Africa. The green colour shows areas of low occurrence risk while the warmer colours show areas with a moderate to a high probability of occurrence.

probabilities of occurrence of the Bellyache bush in the current climate scenario were significantly different (t-stat = 7.83, $p<0.01$) to those predicted by the MaxEnt model in the future.

4. Discussion

We used MaxEnt modelling to examine and characterise the current geographic patterns of the invasive Bellyache bush concerning climate change and other bioclimatic variables in South Africa. Our results indicate that the eastern coastal regions are most susceptible to invasion by Bellyache bush for both the current and future climate scenarios. We observed a pattern where the intensity of invasion increased inland from the eastern coastline because of temperature and precipitation changes in the future. However, the potential mechanisms of spread to explain these different patterns of invasion were beyond the scope of this study. However, a combination of factors including suitable habitats and lack of natural enemies has been reported to influence the distribution and establishment of IAS in a new area (Keane and Crawley, 2002).

Additionally, our field observations suggest that Bellyache bush is often introduced around homesteads as ornaments or natural perimeter hedge and then spreads stochastically to new areas such as rangelands through various seed dispersion mechanisms such as animal or human movement (Moshobane et al., 2017, 2020a). This observation suggests that intentional human introductions and disturbances may be greatly facilitating the invasion currently and possibly in the future (Masocha and Dube, 2017). In the field, we further observed the occurrence of Bellyache bush along the roadsides mostly in the rural areas of the Limpopo province where road maintenance is limited and in clusters within abandoned settlement areas. This suggests that Bellyache bush has the opportunistic behaviour to colonise disturbed areas. Thus, the deliberate introduction of the species in the

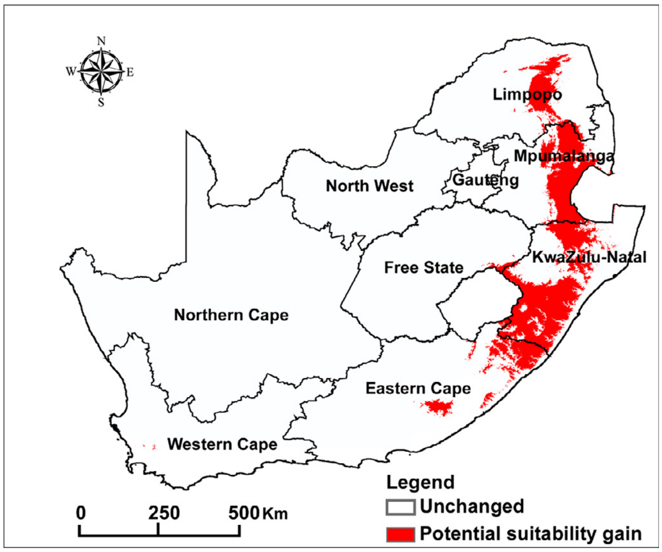

Fig. 6. Potential suitability area gain by Bellyache bush (*Jatropha gossypiifolia* L.) as influenced by climate change. The red colour shows the currently native areas which have huge potential of invasion risk.

agro-natural environments may increase the opportunities and potential invasion by the Bellyache bush (Prentis et al., 2009). These similar patterns of intentional introduction of these alien species by humans have been reported for other invasive alien species, such as *Opuntia fulgida* in Zimbabwe (Masocha and Dube, 2017) and *Lantana camara* (Goncalves et al., 2014). Therefore, bearing in mind the disturbance that Bellyache bush causes to rangelands, and the potential poisoning from their pods (Wu et al., 2019), measures and prohibitive legislation need to be put in place in South Africa to prevent the intentional introduction in areas that were predicted by this current study as potentially suitable areas for invasion by the Bellyache bush. Perhaps, this will curb the further unintentional spread to other districts within the provinces. This approach will help South Africa in achieving its SDG, goal number 15 (Convention on Biological Diversity, 2016)

Furthermore, several pharmacological studies have demonstrated the significant action of different extracts or isolates from Bellyache bush roots and leaves. These extracts have been confirmed to be antimicrobial, anti-inflammatory, anti-diarrhoeal, anti-hypertensive and anti-cancer agents (Félix-Silva et al., 2014; Wu et al., 2019). South Africa could leverage the controlled production or counter-eradication mechanisms by harvesting the already invasive species and converting the products to medicinal purposes.

In addition, our modelling results indicate that temperature variables i.e., temperature seasonality, minimum temperature of the coldest month and the mean annual are the key factors influencing Bellyache bush distribution in South Africa. Bellyache bush requires moderate temperatures and high rainfall areas which are typical of the eastern coastline regions which were predicted by our model. Under climate change, more areas are projected to gain in temperature facilitating suitability of invasion, particularly in most of the inland areas except for the Northern Cape province (Niang et al., 2014). We, therefore, deduce that Bellyache bush habitat suitability is a function of the dynamics of temperature and precipitation which may also be influenced by the altitude of the area. Thus, there is a need for appropriate adaptive management approaches to curb the further spread of the species in the climatically suitable regions.

There is a consensus that invasion risk assessments are useful, particularly as the first line of defence (Keller et al., 2008). In our case, what makes our study different as a risk assessment study from previous research is in the application of a large-scale species distribution modelling framework in a GIS environment to characterise and generate maps showing the spatially specific current and potential future distribution of the invasive Bellyache bush. This approach is robust, timeous and facilitates informed future planning as our results are projected into the future compared to the static physical field assessments (Moyo et al., 2019). Therefore, the information generated in the present work can comprehensively be used for targeted surveillance and control of this invasive species in the country and for informed planning as suggested by the CBD (Convention on Biological Diversity, 2016). Thus, this simple yet robust, modelling approach employed in this study can also be replicated in other countries that are also under threat from the Bellyache bush invasions to aid in the management.

In South Africa, the Bellyache bush is listed as category 1b species (Moshobane et al., 2019). The results from our present study support this listing status. Since the listing in this category requires compulsory control, the species should be prioritised due to the high potential for further spread. Due to the notoriety of the species, proper management approaches are essential, as the spread into many people's homes may lead to human toxin exposures (De Almeida et al., 2015), as reported in previous studies on other Jatropha species (Moshobane et al., 2017).

5. Conclusions

In this study, we leveraged the strength of projecting the global occurrence data of the Bellyache bush to model its spatial distribution in South Africa as a function of bioclimatic factors of the current and future climate scenario. We conclude that the Bellyache bush is mainly found in high rainfall areas and that its distribution is also influenced by temperature seasonality, mean annual temperature range and the minimum temperature of the coldest month. This implies that policies and management strategies for further Bellyache bush invasions in South Africa can now informatively be targeted to high priority areas. Furthermore, the decision to list and prioritise the monitoring of the Bellyache bush species as an important invasive environmental weed in South Africa is now possible.

Declaration of Competing Interest

The authors declare no conflict of interest.

References

Abdelaal, M., Fois, M., Fenu, G., Bacchetta, G., 2019. Using MaxEnt modeling to predict the potential distribution of the endemic plant Rosa arabica Crép. Egypt. Ecol. Inform. 50, 68–75. https://doi.org/10.1016/j.ecoinf.2019.01.003.

Allouche, O., Tsoar, A., Kadmon, R., 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). J. Appl. Ecol. 43, 1223–1232. https://doi.org/10.1111/j.1365-2664.2006.01214.x.

Araújo, M.B., Anderson, R.P., Barbosa, M.A., Beale, C.M., Dormann, C.F., Regan, E., Garcia, R.A., Guisan, A., Maiorano, L., Naimi, B., O'Hara, R.B., Zimmermann, N.E., Rahbek, C., 2019. Standards for distribution models in biodiversity assessments. Sci. Adv. 5, 1–12. https://doi.org/10.1126/sciadv.aat4858.

Ayebare, S., Mdegela, R.H., Nyakarahuka, L., Ndimuligo, S.A., Mwakapeje, E.R., Nonga, H.E., Skjerve, E., Mosomtai, G., 2018. Ecological niche modeling as a tool for prediction of the potential geographic distribution of Bacillus anthracis spores in Tanzania. Int. J. Infect. Dis. 79, 142–151. https://doi.org/10.1016/j.ijid.2018.11.367.

Caminade, C., Medlock, J.M., Ducheyne, E., McIntyre, K.M., Leach, S., Baylis, M., Morse, A.P., 2012. Suitability of European climate for the Asian tiger mosquito Aedes albopictus: recent trends and future scenarios. J. R. Soc. Interface 9, 2708–2717. https://doi.org/10.1098/rsif.2012.0138.

Chemura, A., Mudereri, B.T., Yalew, A.W., Gornott, C., 2021. Climate change and specialty coffee potential in Ethiopia. Sci. Rep. 11, 1–13. https://doi.org/10.1038/s41598-021-87647-4.

Convention on Biological Diversity, 2016. Biodiversity and the 2030 Agenda for Sustainable Development Biodiversity Is Essential for Sustainable Development.

Department of Environmental Affairs, 2004. National environmental management: biodiversity Act 2004 (Act No 10 of 2004): alien and Invasive species list, Government Gazette. 102GOU/B

Elith, J., Hastie, T., Dudík, M., Chee, Y.E., Yates, C.J., Phillips, S.J., 2010a. A statistical explanation of MaxEnt for ecologists. Divers. Distrib. 17, 43–57. https://doi.org/10.1111/j.1472-4642.2010.00725.x.

Elith, J., Kearney, M., Phillips, S., 2010b. The art of modelling range-shifting species. Methods Ecol. Evol. 1, 330–342. https://doi.org/10.1111/j.2041-210X.2010.00036.x.

Félix-Silva, J., Giordani, R.B., Silva-Jr, A.A.Da, Zucolotto, S.M., Fernandes-Pedrosa, M.D.F., 2014. Jatropha gossypiifolia L. (Euphorbiaceae): a review of traditional uses, phytochemistry, pharmacology, and toxicology of this medicinal plant. Evidence-based Complement. Altern. Med. 2014. https://doi.org/10.1155/2014/369204.

GBIF, 2019. GBIF occurence Download. 10.15468/dl.4wxtco

Goncalves, E., Herrera, I., Duarte, M., Bustamante, R.O., Lampo, M., Velásquez, G., Sharma, G.P., García-Rangel, S., 2014. Global invasion of Lantana camara: has the climatic niche been conserved across continents? PLoS ONE 9. https://doi.org/10.1371/journal.pone.0111468.

Hulme, P.E., 2009. Trade, transport and trouble: managing invasive species pathways in an era of globalization. Journal of Applied Ecology 46, 10–18. https://doi.org/10.1111/j.1365-2664.2008.01600.x.

IPCC, 2014. Climate change 2014. Synthesis report. Versión inglés, Climate Change 2014: synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 10.1017/CBO9781107415324

Jardine, S.L., Sanchirico, J.N., 2018. Estimating the cost of invasive species control. J. Environ. Econ. Manage. 87, 242–257. https://doi.org/10.1016/J.JEEM.2017.07.004.

Keane, R.M., Crawley, M.J., 2002. Exotic plant invasions and the enemy release hypothesis. Trends Ecol. Evol. 17, 164–170. https://doi.org/10.1016/S0169-5347(02)02499-0.

Keller, R.P., Frang, K., Lodge, D.M., 2008. Preventing the spread of invasive species: economic benefits of intervention guided by ecological predictions. Conserv. Biol. 22, 80–88. https://doi.org/10.1111/j.1523-1739.2007.00811.x.

Kramer-Schadt, S., Niedballa, J., Pilgrim, J.D., Schröder, B., Lindenborn, 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. Divers. Distrib. 19, 1366–1379. https://doi.org/10.1111/ddi.12096.

Marchioro, C.A., Krechemer, F.S., 2018. Potential global distribution of Diabrotica species and the risks for agricultural production. Pest Manag. Sci. 74, 2100–2109. https://doi.org/10.1002/ps.4906.

Masocha, M., Dube, T., 2017. Modelling Opuntia fulgida invasion in Zimbabwe. Trans. R. Soc. South Africa 72, 217–224. https://doi.org/10.1080/0035919X.2017.1301593.

Mendiburu, F.de, 2019. Agricolae: statistical Procedures for Agricultural Research. https://CRAN.R-project.org/package=agricolae.

Merow, C., Smith, M.J., Silander, J.A., 2013. A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter. Ecography (Cop.) 36, 1058–1069. https://doi.org/10.1111/j.1600-0587.2013.07872.x.

Mesgaran, M.B., Cousens, R.D., Webber, B.L., 2014. Here be dragons: a tool for quantifying novelty due to covariate range and correlation change when projecting species distribution models. Divers. Distrib. 20, 1147–1159. https://doi.org/10.1111/ddi.12209.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being. Island Press, Washington, DC.

Mkunyana, Y.P., Mazvimavi, D., Dzikiti, S., Ntshidi, Z., 2018. A comparative assessment of water use by Acacia longifolia invasions occurring on hillslopes and riparian zones in the Cape Agulhas region of South Africa. Phys. Chem. Earth 112, 255–264. https://doi.org/10.1016/j.pce.2018.10.002.

Mohammadi, S., Ebrahimi, E., Shahriari Moghadam, M., Bosso, L., 2019. Modelling current and future potential distributions of two desert jerboas under climate change in Iran. Ecol. Inform. 52, 7–13. https://doi.org/10.1016/j.ecoinf.2019.04.003.

Moshobane, M..., Mukundamago, M., Adu-acheampong, S., Shackleton, R.T., 2019. Development of alien and invasive taxa lists for regulation in South Africa. Bothalia 1–12.

Moshobane, M.C., Nnzeru, L.R., Nelukalo, K., Mothapo, N.P., 2020a. Patterns of permit requests and issuance regulated alien and invasive species in South Africa for the period 2015–2018. Afr J Ecol 58, 514–528. https://doi.org/10.1111/aje.12720.

Moshobane, M.C., Nelufule, T., Shivambu, T.C., Shivambu, N., 2020b. Occurrence Record of and Possible Invasion by Scarlet Sage (Salvia coccinea Buc ' hoz ex Etl .) in South Africa. Russ J Biol Invasions 11, 393–398. https://doi.org/10.1134/S2075111720040098.

Moshobane, M.C., Wium, C., Mokgola, L.V., 2017. Acuteseeds poisoning in children from Jatropha curcas. SAJCH South African J. Child Heal. 11, 149–150. https://doi.org/10.7196/SAJCH.2017.v11i3.1401.

Moyo, S., Gwitira, I., Murwira, A., Zengeya, F.M., Shekede, M.D., 2019. Spatial distribution and abundance of the African baobab (Adansonia digitata) in Zimbabwe. Trans. R. Soc. South Africa 1–6. https://doi.org/10.1080/0035919X.2019.1650309.

Mtengwana, B., Dube, T., Mudereri, B.T., Shoko, C., 2021. Modeling the geographic spread and proliferation of invasive alien plants (IAPs) into new ecosystems using multi-source data and multiple predictive models in the Heuningnes catchment, South Africa. GIScience Remote Sens. 58, 483–500. https://doi.org/10.1080/15481603.2021.1903281.

Mudereri, B.T., Dube, T., Adel-Rahman, E.M., Niassy, S., Kimathi, E., Khan, Z., Landmann, T., 2019. A comparative analysis of PlanetScope and Sentinel-2 space-borne sensors in mapping Striga weed using Guided Regularised Random Forest classification ensemble. ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 701–708. https://doi.org/10.5194/isprs-archives-XLII-2-W13-701-2019 XLII-2/W13.

Mudereri, B.T., Kimathi, E., Chitata, T., Moshobane, M.C., Abdel-Rahman, E.M., 2020. Landscape-scale biogeographic distribution analysis of the whitefly, Bemisia tabaci (Gennadius, 1889) in Kenya. Int. J. Trop. Insect Sci.. https://doi.org/10.1007/s42690-020-00360-z.

Muposhi, V.K., Gandiwa, E., Chemura, A., Bartels, P., Makuza, S.M., Madiri, T.H., 2016. Habitat heterogeneity variably influences habitat selection by wild herbivores in a semi-arid tropical savanna ecosystem. PLoS ONE 11. https://doi.org/10.1371/journal.pone.0163084.

Muscarella, R., Galante, P.J., Soley-Guardia, M., Boria, R.A., Kass, J.M., Uriarte, M., Anderson, R.P., 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.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J., Urquhart, P., 2014. Africa, in: Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T. E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.W. (eds.. (Ed.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros,. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199–1265. 10.1017/CBO9781107415386.002

Parsons, W.T., Cuthbertson, E.G., 2001. Noxious Weeds of Australia. CSIRO Publishing, Collingwood, Vic.

Phillips, S.J., Dudík, M., Schapire, R.E., 2006. Maxent software for modeling species niches and distributions (Version 3.4.1).

R. Core Team, 2021. R: a language and environment for statistical computing. R Foundation for Statistical Computing,Vienna, Austria. URL https://www.R-project.org/.

Roberts, J., Florentine, S., 2021. Biology, distribution and management of the invasive Jatropha gossypiifolia (Bellyache bush): a global review of current and future management challenges and research gaps. Weed Res.. https://doi.org/10.1111/wre.12504 wre.12504.

Thamaga, K.H., Dube, T., 2019. Understanding seasonal dynamics of invasive water hyacinth (Eichhornia crassipes) in the Greater Letaba river system using Sentinel-2 satellite data. GIScience Remote Sens. 56, 1355–1377. https://doi.org/10.1080/15481603.2019.1646988.

Wu, Q., Patocka, J., Nepovimova, E., Kuca, K., 2019. Jatropha gossypiifolia L. and its biologically active metabolites: a mini review. J. Ethnopharmacol. 234, 197–203. https://doi.org/10.1016/j.jep.2019.01.022.

Zurell, D., Elith, J., Schröder, B., 2012. Predicting to new environments: tools for visualizing model behaviour and impacts on mapped distributions. Divers. Distrib. 18, 628–634. https://doi.org/10.1111/j.1472-4642.2012.00887.x.