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Research Article

PREDICTING THE IMPACTS OF CLIMATE CHANGE ON THE DISTRIBUTION OF CORDIA AFRICANA (LAM.) IN NORTHERN ETHIOPIA

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A B S T R A C T

The recognized significant changes of global climate in recent years has had considerable spatio-temporal impacts on several terrestrial habitats. The objective of this study was to assess climate change impacts on the geographic distribution of *Cordia africana* (*C. africana*) species and identify new potential habitats for its cultivation and conservation up to 2070. MaxEnt species distribution model was used to predict the current and future distribution of this species. A collective of three General Circulation Models ('MIROC5', 'CCSM4' and 'HadGEM2-ES') under scenarios RCP4.5 and RCP8.5 of the 5th IPCC report were used for predicting the future species distribution. The model predicted that approximately 14 – 16% of the total area suitable for the species to grow will be lost under RCP4.5 scenario by 2070. Almost 16 – 17% of the total area suitable for the species will be lost under RCP8.5 scenario by 2070. New suitable areas for the cultivation and conservation of the species will cover approximately 12% and 11 – 14.5% of the total area by 2070 under RCP4.5 and RCP8.5 scenarios, respectively. The conservation strategies for *C. africana* should be of priority and implemented in the species' low impact areas from climate change and new potential areas for the species.

INTRODUCTION

The impacts of global climate change on species and habitats has been a cause of concern to the research community in recent years (Guidigan *et al*., 2018; Makhiya *et al*., 2021; Marchioro *et al*., 2019; Noulekoun *et al*., 2016). Climate change has caused some considerable impacts on the spatial, temporal and biology of terrestrial habitats (Abrha *et al*., 2018; Araujo *et al*., 2011; Jackson and Sax, 2009). For example, changes in climate increase physiological stress on forests, directly leading to increased mortality (Chen *et al*., 2011; Jackson and Sax, 2009). Most forest tree species are adapted to a range of climatic conditions, which is called species' climatic niche (Araujo *et al*., 2011; Marchioro *et al*., 2019) or habitat suitability for the species. Several species has shifted their geographic range due to global warming (IPCC, 2007; Wang *et al*., 2016). The suitable habitats for the species continues to change as the earth warms, for instance, in the tropics, species have been pushed to higher elevations, thereby shrinking their distributions (Chen *et al*., 2011; Jackson and Sax, 2009).

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Therefore, understanding the climatic niches or suitable habitats of forest tree species and predicting their potential shift in spatial distributions over time is very important. This assist with assessing the vulnerability of these species and to develop conservation and management strategies in the face of a changing climate (Guidigan *et al*., 2018; Marchioro *et al*., 2019).

Species Distribution Models (SDMs) can serve as a tool to infer on the climatic niche or habitat suitability of species and the potential shifts in spatial distribution of species as a result of climate change (Elith *et al*., 2006; Idohou *et al*., 2017). SDMs depend on statistical correlation between the species existence and the corresponding environmental and or climatic variables (Phillips *et al*., 2006). The maximum entropy (MaxEnt) model is amongst the most commonly used SDMs to predict species distribution based on species presence-only records (Elith *et al*., 2006; Junior and Nobrega, 2018; Sanchez *et al*., 2010). These species presence-only records can be collected by researchers using a hand held geographic positioning system (GPS) or can be obtained from digital specimen museums and published literature (De Cauwer *et al*., 2014; Phillips *et al*., 2006). The MaxEnt model has been widely used to assess the association between species distribution and determinant variables and to evaluate the potential shifts in climatically suitable habitats for targets species in the face of a changing climate (Abrha *et al*., 2018; Baldwin 2009; De Cauwer *et al*., 2014; Idohou *et al*., 2017; Marchioro *et al*., 2019; Sourabh, 2018). Numerous studies have found out that the MaxEnt model usually outperforms other methods in terms of high tolerance to extremely small sample size, high predictive accuracy and its ability to manage multicollinearity between the environmental variables (Elith *et al*., 2006; Junior and Nobrega, 2018; Phillips *et al*., 2006).

Commonly known as the Cordia, *Cordia africana* (Lam.) is a deciduous forest tree of the Boraginacea family widespread in seventeen countries in Africa (Orwa *et al*., 2009). *Cordia africana* (*C. africana*) is a multipurpose tree, restricted to montane and sub montane habitats with altitudes ranging between 550 and 2600 m.a.s.l. and annual rainfall of 700 to 2000 mm (Gindaba *et al*., 2004; Orwa *et al*., 2009). *C. africana* is one of the threatened tree species in Ethiopia due to the pressure exerted to this species through numerous human-induced activities such as the expansion of agricultural lands (Robi and Edris, 2017; Senbeta and Denich, 2006), habitat destruction for road construction and urbanization, timber harvest and fuelwood collection (Robi and Edris, 2017; Zenebe *et al*., 2012). Furthermore, overharvesting and over-grazing are the main factors that reduce the population status and the distribution of this species over time (Amente, 2017; Robi and Edris, 2017; Zenebe *et al*., 2012). In Ethiopia, the tree is of great importance due to its numerous socio-economic, nutritional, medicinal, ecological and environmental benefits (Gebreegziabher, 2014; Markos and Simon, 2015; Tewolde-Berhan *et al*., 2015; Yohannes *et al*., 2015). It also plays a great role in agro-silvopastoral systems, facilitate bee keeping and act as a source of shade to other crops (Mekonnen *et al*., 2006; Robi and Edris 2017; Teklay, 2005). Therefore, considering the socio-economic, medicinal and environmental benefits of *Cordia africana* in Ethiopia, its current and future distribution is worthy of attention. Understanding the current and future distribution of these threatened-multipurpose tree species in northern Ethiopia, conservation strategies aimed to prevent its further habitat loss can be done more precisely. The aim of this study was therefore to predict the current and future climatic distributions of *Cordia africana* species and to identify some new potential habitats of this species for its cultivation and conservation in the face of a changing climate.

MATERIALS AND METHODS

Study area

The study area covers the Tigray region, in the northern part of Ethiopia. Tigray region is located between 12°15'N and 14°57'N latitude and 36°27'E and 39°59'E longitude, and has an estimated area of 53,638 square kilometers (Fig. 1b). It has an average annual precipitation ranging between 500-1000 mm and annual mean temperature ranging from 12°C in the highlands up to 37°C in the lowlands (Tonini *et al*., 2012). The elevation ranges between 600 and 3434 ma.s.l. and the area falls into an arid environment (Meaza and Demssie, 2015; Tonini *et al*., 2012). The vegetation cover of the study area include tree and shrub species with common tree species including among others, *Cordia africana, Faidherbia albida, Acacia etbaica, Acacia abyssinica, Eucalyptus* spp., *Schinus molle, Opuntia ficus-indica, Agave sisalana*, *Euphorbia* spp. (Markos and Simon, 2015; Meaza and Demssie, 2015).

Sampling

A review of literature was used for understanding the specific geographic areas to visit where the population of *Cordia africana* species was reported to occur in Tigray region (Gebreegziabher, 2014; Tewolde-Berhan *et al*., 2015). During field visits, a handheld GPS (Garmin) was used to collect a total of 200 presence-only data for *C. africana* in the study area. These data was collected with spatial scale of 30 arc seconds (~ 900 × 900 m), recorded in terms of coordinate pair as decimal latitude/longitude and used as input to the MaxEnt model.

Environmental variables

Three bioclimatic variables (precipitation of wettest quarter, precipitation of driest month and temperature seasonality) for *C. africana* habitat were downloaded from the WorldClim database (http://www.worldclim.org/bioclim), with 30 arc seconds spatial resolution. These variables have been derived from measurements of monthly temperature and rainfall from weather stations across the globe, over a period of 1950-2000 (Hijmans and Graham, 2006) and Makhiya *et al*. (2021) reported that these bioclimatic variables have a strong relationship with the distribution of *Cordia africana* species in the protected areas of northern Ethiopia. The variables are commonly used in species distribution modelling (De Cauwer *et al*., 2014; Elith *et al*., 2006; Marchioro *et al*., 2019; Sohel *et al*., 2016) due to their strong relationship with species growth, development and distribution. In addition to the bioclimatic variables, the slope layer was produced from the Digital Elevation Model (DEM) downloaded from the SRTM-Shuttle Radar Topography Mission (http://www2.jpl.nasa.gov/srtm/) and soil layer was downloaded from the Food and Agriculture Organization (FAO) website. Slope and soil layers have been observed to be influencing the distribution of *Cordia africana* species in the protected areas of northern Ethiopia's dry lands and in some parts of Africa (Makhiya *et al*., 2021; Orwa *et al*., 2009). The soil layer was resampled to 30 arc seconds spatial resolution using ArcGIS version 10.4 (ESRI, Redlands, CA, USA) software and was used as input to the MaxEnt model together with the slope, bio 16 (precipitation of the wettest quarter), bio 14 (precipitation of the driest month) and bio 4 (temperature seasonality) variables (Tab. 1).

Climate data used for predicting the future distribution of *C. africana* was downloaded from WorldClim database (http://www.worldclim.org/cmip5_30s). This data was downloaded for the years 2050 (average of 2041-2060 period) and 2070 (average of 2061-2080 period). This data has been predicted by the WorldClim organization using a total of nineteen General Circulation Models (GCMs) under four greenhouse gas concentration scenarios called Representative Concentration Pathways (RCPs). An average layer of three GCMs, namely: Community Climate System Model 4 (CCSM4), Hadley Global Environment Model 2 – Earth System (HadGEM2-ES) and Model for Interdisciplinary Research on Climate 5 (MIROC5) was computed in ArcGIS and used for this study, under scenarios RCP 4.5 and RCP 8.5. RCP 4.5 represents a relatively stable scenario where the total radiative forcing reaches 4.5 W m^{-2} by 2100 and further stabilizes as a result of green technologies adoption (Van Vuuren *et al*., 2011). On the other hand, in RCP 8.5, emissions continue to increase throughout the 21st century and the total radiative forcing is predicted to reach up to 8.5 W m^{-2} by 2100 (Upadhyay *et al*., 2018). Climate change impact on the distribution of *C. africana* species was evaluated using the DIVA-GIS software through overlaying and reclassifying rasters of current and future potential distribution areas. This impact was analyzed considering the following four likely conditions for each cell as described by Scheldeman and Van Zonneveld (2010): (i) "high impact areas: areas where a species potentially occurs in the present climate but which will not be suitable anymore in the future; (ii) areas outside the realized niche: areas that are neither suitable under current conditions nor under future conditions (as predicted); (iii) low impact areas: areas where the species can potentially occur in both present and future climates; and (iv) new suitable areas: areas where a species could potentially occur in the future, but which are not suitable for natural occurrence under current conditions".

MaxEnt model

Maximum Entropy (MaxEnt) model for species' distribution modelling is a machine learning system or algorithm that estimates the probability distribution for a species' occurrence based on environmental constraints (Phillips *et al*., 2006). The model makes use of both ecological (species occurrence) and climatic (environmental) data to find out the distribution of species (Baldwin, 2009; Guidigan *et al*., 2018). Features within the MaxEnt model are derived from environmental variables that are in the categorical or continuous form (Elith *et al*., 2006). In this study, this model was run for the current and future (2050 and 2070) species distributions. When building the model, 80% of the data was randomly selected and used for training and the remaining 20% was used for testing. 80% and 20% was used for this study instead of the 75% and 25% which is normally used for training and testing the model respectively, because using a relatively higher percentage of training data enables the model to be well trained, hence improving its accuracy in predictions (Xu *et al*., 2018). A bias file was also used to reduce the biasness of the model in predictions (Phillips *et al*., 2006).

The number of iterations was set to 15 and the maximum number of background points was set to 10000, and the remaining settings were left at their default values (Xu *et al*., 2018). The robustness of the model in predicting the distribution of the species in the study area was evaluated using the random test percentage setting in MaxEnt together with the area under the receiver operating characteristic (ROC) curve (AUC) which also serves as a threshold-independent measure of the model sensitivity and specificity (Phillips *et al*., 2006). The ten percentile training presence threshold generated by the model was applied to the predicted species distribution maps in order to obtain the binary presence (1) and absence (0) maps which display the suitable and unsuitable habitats for the species (Phillips *et al*., 2006). This threshold assumes that geographic locations with a probability above the threshold have climatic conditions suitable for the species occurrence while on the other hand, the species would not occur in the geographic locations below the threshold (Guidigan *et al*., 2018). Moreover, the current species' suitability was classified using the four probability classes defined by Noulekoun *et al*. (2016): no suitability (<0.18), very low suitability (0.18-0.36), low suitability (0.36-0.54), medium suitability (0.54-0.72) and high suitability (>0.72).

RESULTS

Current distribution of *Cordia Africana*

The evaluation results shows that the performance of the model applied was high, with a mean AUC value of 0.77, indicating an acceptable performance of MaxEnt model in estimating the distribution of *Cordia africana*. The percent contribution and permutation importance shows that temperature seasonality (standard deviation * 100) (bio_4) and precipitation of Wettest Quarter (bio_16) are the strongest variables in predicting the distribution of *C. africana* species (Tab. 1). Moreover, the three jackknife tests results also showed that temperature seasonality (standard deviation * 100) and precipitation of Wettest Quarter are the most important variables in predicting the distribution of *C. africana*. This is so because, for the training gain, bio_4 showed more gain to the model when used in isolation (blue bars) (Fig. 2a). On the other hand, for the test gain and the AUC gain, bio_16 showed a decrease in the model gain when omitted from the model (light blue bars) (Fig. 2b & 2c).

Table 1 Input variables for MaxEnt model and the percentage contribution (%) and permutation importance (%) for each variable

Code	Environmental variable	Unit	Percentage contribution (%)	Permutation importance (%)
bio_4	Temperature Seasonality (Standard Deviation) * 100	CV	43.3	37.2
bio_16	Precipitation of Wettest Quarter	mm	39.6	36.7
slope	Slope	%	8.4	13.1
soil_typ	Soil type	-	4.6	7.2
bio_14	Precipitation of Driest Month	mm	4.1	5.7

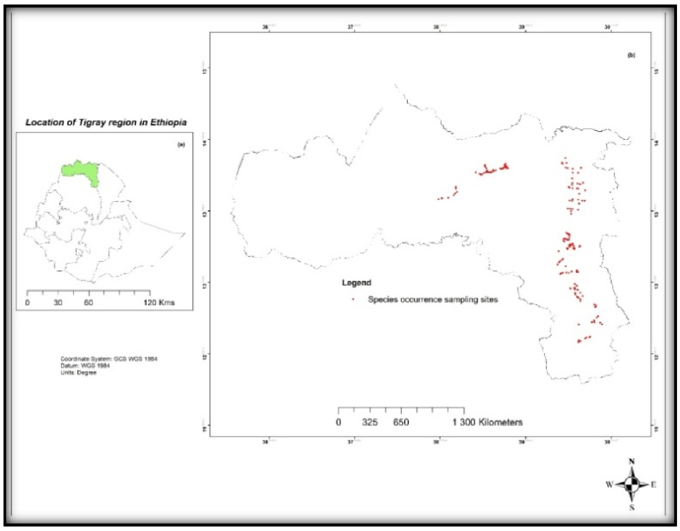

Figure 1- (a) Location of the study area (green) in Ethiopia; (b) Geographic location of sampling sites (red) within the study area.

The model predicted that *Cordia africana* species occurs in geographic areas with precipitation of Wettest Quarter ranging between 130 and 310 mm and the suitability of the species decreases in those areas with precipitation of Wettest Quarter beyond 310 mm. The model has predicted the species to be widely spread in areas with temperature seasonality ranging between 11.4 and 15.9°C. The suitability of the species decreases with the temperature seasonality beyond 16°C and these areas are normally of very low suitability to no suitability (Fig. 3a).

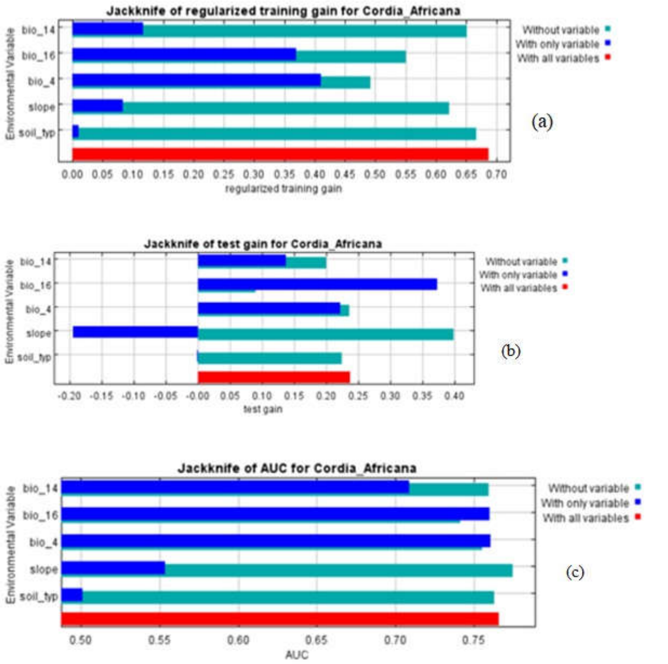

Figure 2 Jackknife test results of the relative importance of the environmental variables based on: (a) the training gain; (b) the test gain; and (c) the AUC gain. Light blue color (without variable); Dark blue color (with only variable); and red color (with all variables).

Moreover, the species occurs mainly in areas with slope ranging between 16 and 47% and the species suitable habitats increases with increasing precipitation of driest month. The model also predicted major soils such as Lithosols, Eutric Cambisols, Chromic Luvisols, Chromic vertisols and Chromic Cambisols to be suitable for the species distribution in the study area. According to the map of species' suitability (Fig. 3b), 1716153.98 hectares (ha) (31.4%) of the study areas is suitable for *C. africana* species and the remaining 3756703.04 ha is not suitable for the species. The predicted suitable habitats for the species are widely spread throughout the study area, covering both the lowlands, mid and highlands. Even though the species has been predicted to be widely spread throughout the study area, according to the map of species' suitability (Fig. 3a), 68.6% of the area is of no suitability, 15% is of very low suitability, 8% is of low suitability, 5% is of medium suitability and the remaining 3.4% of the study area is of high suitability.

Future distribution of Cordia Africana

The species distribution pattern for years 2050 (average of 2041-2060 period) and 2070 (average of 2061-2080 period) was projected using an average layer of 'MIROC5', 'CCSM4' and 'HadGEM2-ES' under scenarios RCP 4.5 and RCP 8.5. The results showed that under RCP 4.5 scenario, 13.7% of the total area suitable for *Cordia africana* species will be affected by climate change while on the other hand, 14.3% of the total area will remain climatically stable by 2050 (Tab. 2). Unsuitable areas for the species will reduce from 68.6% to 59.9% by 2050, owing to the new suitable areas for the species which will cover 12.1% of the total area (Fig. 4b). The model predicted that by 2070, 15.5% of the total area will be affected by climate change and unsuitable areas for the species will decrease by 9% from the current species' unsuitable areas. Moreover, 12.5% will remain still remain climatically stable and 12.4% of the total area will be covered by the new areas for the conservation and cultivation of the species by 2070 (Fig. 4c).

Table 2 Area in ha (%) covered by different impact areas under future projections

Scenario	High impact areas (%)	Areas outside the realized niche (%)	Low impact areas (%)	New suitable areas (%)
RCP 4.5_2050	752461.03 (13.7)	3277240.61 (59.9)	779940.9 (14.3)	663214.48 (12.1)
RCP 4.5_2070	846917.83 (15.5)	3263206.55 (59.6)	685484.1 (12.5)	677248.54 (12.4)
RCP 8.5_2050	930786.06 (17.0)	3338166.93 (61.0)	601615.87 (11.0)	602288.16 (11.0)
RCP 8.5_2070	974316.86 (17.8)	3148497 (57.5)	558085.07 (10.2)	791958.09 (14.5)

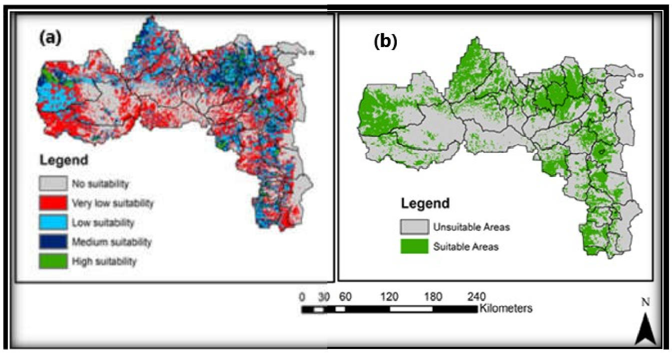

Figure 3 MaxEnt model predictions for the current distribution of *C. africana* in the study area: (a) without threshold; and (b) with a threshold applied

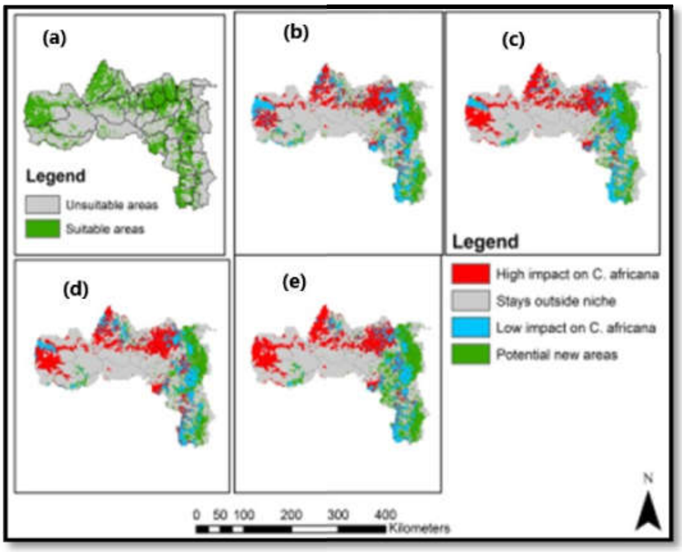

Figure 4 Climate change impacts on *C. africana* species within the study area: (a) Current species 'suitability; (b) Future species' distribution by 2050 under scenario RCP 4.5; (c) Future species' distribution by 2070 under scenario RCP 4.5; (d) Future species' distribution by 2050 under scenario RCP 8.5; and (e) Future species' distribution by 2070 under scenario RCP 8.5.

The results showed that even for the RCP 8.5 scenario, the same trend has been predicted. For example, 17% of the total area suitable for *Cordia africana* species will be affected by climate change and 11% of the total area will remain climatically stable by 2050 (Tab. 2). Unsuitable areas for the species will also reduce from 68.6% of the current species' distribution to 61% by 2050, due to the new suitable areas for the species which will cover 11% of the total area (Fig. 4d). The model predicted that by 2070, 17.8% of the total area will be affected by climate change and unsuitable areas for the species will also decrease by 11.1% from the current species' unsuitable areas. Likewise, 10.2% will remain still remain climatically stable and 14.5% of the total area will be covered by the new areas for the conservation and cultivation of the species by 2070 (Fig. 4e). Generally, MaxEnt model predicted that between 5 – 9.45% of the suitable areas for *C. africana* will be affected by climate change across all the scenarios until 2070, particularly the western and central (Kafta Humera, Asgede Tsimbla, Laelay Maychew, Medebay Zana, Adwa districts, etc.) parts of the study area. While this is so, new suitable areas for the species will be more pronounced in the eastern (Erob, Saesie Tsaeda Emba, Gulumekeda, Atsbi Wemberta, Hintalo Wejirat and Raya Azebo districts) parts of the study area.

DISCUSSION

The results of this study showed that the presence of *C. africana* is currently limited to precipitation of Wettest Quarter ranging between 130 and 310 mm and temperature seasonality ranging between 11.4 and 15.9°C. Similar results were observed for precipitation of Wettest Quarter and temperature seasonality being very important variables in predicting the distribution of *Cordia africana* species in the protected areas of northern Ethiopia (Makhiya *et al*., 2021) and other tree species elsewhere (De Cauwer *et al*., 2014; Guidigan *et al*., 2018). The results of this study showed that *C. africana* was observed to increase in slopes of 16 to 47%. The results of this study are consistent with the findings by Yohannes *et al*. (2015) who reported that the distribution of *C. africana* species in the southern parts of Ethiopia was found in slope gradient varying between 15 and 50% (Kebede *et al*., 2013). One of the reasons the MaxEnt model predicted the species to be limited to moderate slopes (16-47%) might be due to the northern part of Ethiopia being situated in mountainous region and in this areas moderate to high-slopes receive the highest solar radiation due to direct incoming radiation (Zeng *et al*., 2014). High or strong solar radiation results in less soil moisture and drought-tolerant plants such as *Cordia africana* are not limited in growing in such areas (Orwa *et al*., 2009). The results of this study revealed that *C. africana* is more dominant in Lithosols, Eutric Cambisols, Chromic Luvisols, Chromic vertisols and Chromic Cambisols in that order, which is consistent with the findings by Orwa *et al*. (2009) on the distribution of *C. africana* species in Africa.

The results of this study revealed that climate change will affect between 5 – 9.45% of the total area of the species' suitable habitats by 2070 across all the scenarios. The MaxEnt model predictions showed that the species will shift towards the eastern parts of the region for all the scenarios (RCP 4.5 and RCP 8.5) and time periods (2050 and 2070). The results of this study are in agreement with the findings by Noulekoun *et al*. (2016) and Makhiya *et al*. (2021) who reported that impacts of climate change in northern part of Ethiopia will force the *Faidherbia albida* and *Cordia africana* species respectively, to shift to the eastern part of the region by the end of the century RCP 8.5. The model revealed that the current distribution of *C. africana* species thrives in geographic locations with temperature seasonality ranging between 11.4 and 15.9°C and precipitation of Wettest Quarter ranging between 130 and 310 mm. However, as the earth warms, the model predictions showed that it will be restricted to temperature seasonality ranging between 15.4 and 17°C, and precipitation of Wettest Quarter ranging between 210 and 388.5 mm, hence, the species will not prefer areas with very high or low rainfall and temperatures.

One of the reasons for this observed pattern on the future distribution of *C. africana* is that germination of its seedling is usually on temperatures ranging from 20 to 30°C and for temperatures below 15°C, germination is prohibited (Whitmore, 1998). This is so, as for example, the species will shift from areas of high temperatures such as Kafta Humera district to eastern parts (Endamehoni, Saesie Tsaeda Emba, Ganta Afeshum, Gulomekeda, Alamata and Atsbi Wemberta districts) of the study area which are of currently very low temperatures and will increase in temperatures as the region warms, hence becoming suitable habitats for this species. The results of this study are in consistency with the results by other researchers who reported that climate change will cause a shift on tree species distribution (Abrha *et al*., 2018; Idohou *et al*., 2017; Noulekoun *et al*., 2016; Sanchez *et al*., 2010; Scheldeman and van Zonneveld, 2010) across the different parts of the world. The eastern parts of the study area and other areas which will remain climatically stable until 2070 will be of great importance for the conservation and cultivation of the threatened-multipurpose *C. africana* species. This is so because Sanchez *et al*. (2010) observed that artificial cultivation is one of the effective tools for restoring and conserving threatened plant species in order to face the challenge brought by global climate change, for sustainable development.

CONCLUSIONS

The current trend in climate change will cause small parts of the habitats for *Cordia africana* (*C. africana*) species to be lost by 2070. In the meantime, small parts of the geographic locations will also emerge as new potential habitats for the species by 2070, more so that, in general, the species does not seem to experience a significant reduction in its distribution within the study area. The habitats for the threatened-multipurpose *C. africana* species are likely to face additional threats in the near future due to the impacts of increasing greenhouse gas emission coupled with anthropogenic disturbance. The results of this study can help in conservation strategies (i.e., cultivation) designed specifically for the expected changes in vegetation species' distribution under a changing climate. Therefore, further studies, particularly on threatened-multipurpose species are recommended and using the ensemble species distribution models, an ensemble of general circulation models and additional variables such as human activities and the occurrence of extreme events (fires and floods) which could also cause further decrease of suitable habitats for *C. africana* species.

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