Short title: Distributions of tree species under climate changes

Predicting the distributions of *Pouteria adolfi-friederici* and *Prunus africana*

iconic tree species under current and future climate change scenarios in

Ethiopia

Zerihun Tadesse^{1,2*}, Sileshi Nemomissa¹, Debissa Lemessa¹

¹Department of Plant Biology and Biodiversity Management, College of Natural and Computational Sciences, Addis Ababa University, Ethiopia

²Department of Plant Science, College of Agriculture, Wollega University, Ethiopia

*Corresponding author: Email: zerihunbio@gmail.com, Mobile phone: 0911080458.

Abstract

The distributions of the potential adaptive ranges of iconic plant species are not yet fully known especially in regions such as Ethiopia where high climatic variability and vegetation types are found. This study was undertaken to predict the distributions of the potential suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* tree species under the current and two future climate scenarios (i.e., RCP 4.5 and RCP 8.5 in 2050 and 2070) using MaxEnt software (version: 3.4.4.). Eleven less correlated environmental variables ($r < 0.7$) were identified and used to make the prediction models. Elevational shifts of the highly suitable habitats, effects of elevation, solar radiation and topographic position in relation to the current and future climatic scenarios on the habitats were statistically analyzed using independent t-test and linear model. Under all climate scenarios, we found a decrease in the proportion of areas of highly suitable habitats for both study species. High potentials of suitable habitats for *Pouteria adolfi-friederici* are predicted to be confined to southwest, west central and south parts of Ethiopia in fragmented moist afro-montane forest patches, while it is in the southwest and west central parts of Ethiopia for *Prunus africana*. On basis of vegetation types of the country, potential suitable habitats for *Pouteria adolfi-friederici* are predicted to occur in moist evergreen forest, dry evergreen forest and grassland complex and *Combretum-Terminalia* woodland vegetation types. Whereas, moist evergreen forest, dry evergreen forest and grassland complex and riverine vegetation types are predicted to comprise potential suitable habitats for *Prunus africana*, showing considerable spatial dynamics. Overall, our results suggest that the strategies deem to design biodiversity conservation should take into account the dynamics of the suitable niches of different species under different future climate scenarios.

Keywords: adaptive range, climate change, Ethiopia, prediction model, habitat suitability, range shift, species distribution.

Introduction

Plant species have their optimum range of climatic condition to survive in their ecological zones [1]. Among others, the environmental factors limiting the adaptive range of the plant species are altitude, temperature, moisture, and soil types [2,3]. Climate, which represents a weather condition over a wide environment for a long period, plays important role to determine the distribution of plant species in their suitable ecological regions [2]. Temperature and precipitation are the most important environmental variables determining the climatic condition of ecological regions to which plant species are naturally adapted to grow [4]. Temperature and

moisture can change as a result of climate change and challenge populations of a species already well adapted to the climatic conditions of ecological regions for long period [3].

However, different studies are depicting that climate change is taking place over the world due to global warming [5–12]. Climate change is mainly caused by increasing global temperature [13–15] that is initiated mainly due to greenhouse gas (GHG) emissions from multiple sources [16–18]. Thus, a change in global temperature and precipitation [19,20] can affect the distribution of global biodiversity in the future [21–23]. Plants can change their range of distribution to respond to the climate change [24–26] and either go extinct [27] or there would be shifting out from of their current ecological niches to new ecological areas [28,29].

Pouteria adolfi-friederici and *Prunus africana* tree species, which belong to Sapotaceae and Rosaceae families respectively, are iconic trees occurring in remnant fragments of moist and dry afromontane forests. The species are currently existing in scattered patterns with limited number in some agricultural landscapes of Ethiopia [30–32]. *Pouteria adolfi-friederici* is a timber tree that can grow up to 50 m, having a clear straight bole usually reaching over 16 m height with narrow conical canopy in moist afromontane forests within altitudinal range of 1350–2450m a.s.l in Ethiopia [31]. Its seeds are recalcitrant and sensitive to desiccation and need to be sown while they are in fresh condition [33–35 and effective germination thereof demands optimum temperature and moisture.

The other iconic tree species that has overlapping niche with *Pouteria adolfi-friederici* is *Prunus africana*. *Prunus africana*, the African cherry, is a valuable timber tree growing up to 40 m high with a diameter of 1m in moist and dry afromontane forests [33]. Similar to *Pouteria adolfi-friederici*, seeds of *Prunus africana* are recalcitrant and loose viability in a short period of time when exposed to low moisture condition. The bark extract of this species is used to treat benign

prostatic hyperplasia and has drawn a considerable commercial interest [36]. Therefore, these two indigenous tree species, *Pouteria adolfi-friederici* and *Prunus africana*, were selected in our study mainly for three fundamental reasons: firstly, their seeds cannot be conserved in low temperature or in cold gene bank and, thus, they can only be conserved at their natural habitats or niches; secondly, the species have remarkable ecological and economic significance; and thirdly, *Prunus africana* is assessed as vulnerable [37,38] and the populations of both species are under extensive overexploitations for various uses. Moreover, previous studies have focused on phylogeography and medicinal uses of *Prunus africana* [36,39,40] and only limited study was conducted on *Pouteria adolfi-friederici*. Afromontane forests of Ethiopia where these iconic tree species are mainly confined to have been under immense threat due to deforestation problem [41–43]. The deforestation has resulted in diminishing of suitable habitats of these important tree species although their potential distributions in Ethiopia under climate change is not yet well known. Thus, studying the potential suitable habitat distributions of the species could have informed decisions for their conservation interventions. Therefore, the aim of this study was to understand the distributions of *Pouteria adolfi-friederici* and *Prunus africana* tree species under the current climatic condition and predict their potential suitable habitats using two climate change scenarios (RCP 4.5 and RCP 8.5 in 2050 and 2070). Here, we hypothesized that, (1), there are unoccupied suitable niches under the current climatic condition for both species in ecosystems where previously no geographical detections were addressed, (2) there will be range shifts in distributions of potential suitable habitats for both species in the future beyond the moist and dry afromontane forests ecosystems, emanating from the changes in climatic conditions.

Materials and Methods

Study system

The study was undertaken within the geographical area of Ethiopia, which lies between 3°24'–14° 53' N and 32° 42'–48°12' E (Fig 1). The total area of Ethiopia is 1.13×10⁶ square km and this is approximately equal to 113,289,457 ha within the elevational range of 124 m b.s.l. to 4560 m a.s.l.

Fig 1. The current occurrences of *Pouteria adolfi-friederici* and *Prunus africana* tree species across five major vegetation types of Ethiopia.

Historically, the vegetation of Ethiopia has been classified in several ways, but, recently [32] has classified into 12 potential vegetation types. In the study of [44], these 12 potential vegetation types have been classified into five major vegetation groups (Fig 1 and Table 1) for conservation purposes, and we have used them for this study.

Table 1: Five major vegetation groups from the 12 potential vegetation types of Ethiopia

Grouped 5 major vegetation types	Vegetation types as classified in the study [32]
<i>Acacia-Commiphora</i> woodland	<i>Acacia-Commiphora</i> woodland and bushland (ACB); Acacia wooded grassland (ACB); Desert and semi-desert scrubland (DSS)
<i>Combretum-Terminalia</i> woodland	<i>Combretum-Terminalia</i> woodland and wooded grassland (CTW); Wooded grassland of the Western Gambela region (WGG)
Dry Afromontane Forest (DAF)	Dry evergreen Afromontane Forest and Grassland complex (DAF)

	Afro-Alpine vegetation (AA); and Ericaceous Belt (EB);
Moist Afromontane Forest (MAF)	Moist Evergreen Afromontane Forest (MAF); Transitional Rain Forest (TRF)
Others	Salt Pans, Saline/brackish and Intermittent wetlands and Salt-lake Shore Vegetation (SLV/SSS); Salt Lake open water vegetation (SLV/OW); Freshwater marshes and swamps, Floodplains and Lake Shore vegetation (FLV/MFS); Freshwater lakes - open water vegetation (FLV/OW)

Method

The species occurrences data of both species were collected from the National Herbarium of Ethiopia and from GBIF (www.gbif.org). Moreover, geographical coordinates of species presence locations were collected using a handheld Garmin GPS in west central areas of the country during a field work. In total, 94 coordinates (i.e., 30 for *Pouteria adolfi-friederici* and 64 for *Prunus africana*) points were used in this study.

As the current input data, the 19 bioclimatic variables (1970–2000) with a spatial resolution of about 1 km² were downloaded from www.worldclim.org/data/worldclim21.html. Furthermore, solar radiation index (sri) was downloaded from www.worldclim.org/data/worldclim21.html while indices of topographic position and elevation data were downloaded from <http://www.earthenv.org/topography>.

The input data for future climate scenarios of the Coupled Model Inter-comparison Project phase (CMIP5) was used as stated in the studies [45,46]. Here, the downscaled data of Representative

Pathways with intermediate (RCP 4.5) and highest concentrations (RCP 8.5) of two periods (2050 and 2070) were downloaded from http://www.worldclim.com/CMIP5_30s. These trajectories are based on their radiative forces (w/m^2) and are expected to change at the turn of the century [47,48].

Data analysis

Environmental variables were clipped into Ethiopian boundary shape file using ArcGIS (version: 10.5) and converted into ASCII format using SDMTtoolbox 2.4 [49]. The multicollinearity (i.e., the unnecessary correlation among the predictor variables) was checked for the current data of 19 bioclimatic variables using the pairwise correlation matrix with Pearson correlation analysis (Table in S1 Table). Eleven variables that are less correlated ($r < 0.7$) were included in prediction models and this cut-off point was commonly applied to fit models to bioclimatic data [50–52].

The 11 bioclimatic variables used in the prediction models are mean monthly temperature, isothermality, temperature seasonality, mean temperature of coldest quarter, precipitation seasonality, precipitation of driest quarter, precipitation of warmest quarter, precipitation of coldest quarter, elevation, solar radiation index and topographic position index.

The species distribution modelling was run with MaxEnt software (version: v.3.4.4., R Core Team, 2021). The modelling was performed with a random test percentage at 25%, regularization multiplier 1, maximum background points of 10,000, maximum iterations at 5000, convergence threshold held at 0.00001 and 10 replicates with averaged results. The model was evaluated by calculating the AUC of ROC graph [53–56]. Concerned average value of AUC graph < 0.7 is bad, 0.7–0.8 is good and 0.9–1 is excellent for the species distribution modelling as explained in the study [57].

To analyze habitat suitability, the output maps of 10 replicate runs (0.0–1.0 categories) were used in ArcGIS. Accordingly, five habitat suitability classes were identified as highly suitable (0.85–1.00), suitable (0.69– <0.85), moderately suitable (0.54– <0.69), less suitable (0.38– <0.54) and unsuitable (0.0– <0.38), based on range values of band categories. The area extents were computed in hectare (ha) from the number of pixels counts for each suitable habitat classes. The change in the proportion of the habitats under current and future climate change scenarios (RCP 4.5 and RCP 8.5) was analyzed by overlying MaxEnt output maps over the shape files of the vegetation classes of Ethiopia. Predicted geographic areas in Ethiopia were extracted from Ethiogis database and the area of each was calculated using ArcGIS (version: 10.5).

Model performance evaluation

The model outputs for both *Pouteria adolfi-friederici* and *Prunus africana* tree species indicated that all the test omission rates averaged over ten replicate runs were close to the predicted omission on the training and test rates under the current and future conditions. The average AUC for *Pouteria adolfi-friederici* showed great model fit under the current (0.926), RCP 4.5 (0.911, 0.903) and RCP 8.5 (0.901, 0.910) scenarios, at 2050 and 2070. Average AUC for *Prunus africana* also indicated very good model fit under the current (0.887), RCP 4.5 (0.868, 0.880) and RCP 8.5 (0.885, 0.896) scenarios, at the 2050 and 2070.

The differences in elevational shifts of the habitat suitability categories under current and future climatic scenarios were tested using independent t-test as implemented in R version: 4.1.0. [58]. Moreover, three environmental variables, namely, elevation, solar radiation index and topographic position index, the values of which do not vary across the climatic scenarios, were used to statistically analyze their effect on the different categories of habitat suitability using linear model in R.

Results

Habitat suitability mapping and modelling

The environmental variables significantly contributing to the distributions of habitat suitability of *Pouteria adolfi-friederici* were solar radiation, precipitation of warmest quarter, precipitation of driest quarter, precipitation seasonality, mean temperature of coldest quarter and elevation. Similarly, solar radiation, precipitation of warmest quarter, mean temperature of coldest quarter and mean monthly temperature significantly contribute to determine the distribution of *Prunus africana* under the current (1970–2000) and future (2050 and 2070) climate scenarios (Table 2).

Table 2: The contributions of environmental variables (%) in spatial prediction models of suitable habitats under the current and future climate scenarios of 2050 and 2070 periods.

Variable	<i>Pouteria adolfi-friederici</i>					<i>Prunus africana</i>				
	Current	RCP 4.5		RCP 8.5		Current	RCP 4.5		RCP 8.5	
	climate	2050	2070	2050	2070	climate	2050	2070	2050	2070
Sri	51.2	39.1	50.8	46.7	51.1	64	57.5	62.1	63.5	58.5
Bio_18	16.3	13.8	16	11.7	10.2	6	10.6	10.1	5.7	4.5
Bio_15	10.5	13.3	8.2	7.8	8.5	0.2	0.1	0.3	0.2	0.1
Bio_11	7.4	1.9	3.8	3.6	4	12.4	9.6	10.5	12.6	13
elev	5.5	1.2	1.5	1.5	2.1	4.7	3.3	3.2	3.3	3.3
Bio_04	3.1	2.9	2	0.7	0.6	0.7	0.5	0.4	0.7	0.3
Bio_19	2.8	2.4	2.5	1.7	3.3	3	5.6	3.3	1.8	7.5
Bio_02	1.5	8.5	6.3	5.8	5.2	1.4	10.5	7.1	9.8	10.2
Bio_17	1.2	13.8	6.7	17.7	12.4	1.1	0.6	1.2	0.8	0.7

tpi	0.3	0.4	0.2	0.1	0.4	0.4	1.3	0.5	0.4	0.4
Bio_03	0.1	2.7	2	2.7	2.2	6.2	0.4	1.4	1.1	1.6

*elev: elevation, sri: solar radiation index, tpi: topographic position index.

Response curves are good informative and indicators for environmental variables contributing to the high probability of the occurrence of habitat suitability for species. The occurrence of highly suitable habitats of *Pouteria adolfi-friederici* was predicted in the range of 15,400–16,200 nm solar radiation, 30–50 mm of Precipitation Seasonality, 170–250 mm Precipitation of Driest Quarter and 500–700 mm Precipitation of Warmest Quarter (Fig 2).

Fig 2. Response curves of four top contributing variables to distribution of *Prunus adolfi-friederici*: solar radiation, precipitation of warmest quarter, precipitation of driest quarter and precipitation seasonality.

Similarly, highly suitable habitat for the distribution of *Prunus africana* was predicted between 15,400–16,200 nm of solar radiation, 7.5–15.5°C mean temperature of coldest quarter, 400–700 mm precipitation of warmest quarter and elevation in 2250–2700 m a.s.l. (Fig 3).

Fig 3. Response curves of four top contributing variables to distribution of *Prunus africana*: solar radiation, mean temperature of coldest quarter, precipitation of warmest quarter and elevation.

Habitat suitability mapping under the current climate conditions (1970–2000)

Five habitat suitability classes were identified, i.e., highly suitable, suitable, moderately suitable, less suitable and unsuitable with different area proportions mapped for the two study species.

Both moderately and less suitable habitats are areas with unfavorable conditions for both species under the current climate conditions. The distributions of highly suitable and suitable habitats of *Pouteria adolfi-friederici* are largely concentrated in southwest and with a relatively smaller amount in the southeastern part of Ethiopia (Fig 4). For *Prunus africana*, highly suitable and suitable habitats cover most of the central, eastern and western highlands of Ethiopia (Fig 5).

Fig 4. Spatial prediction models of the distributions of habitat suitability for *Pouteria adolfi-friederici* under current and future climate scenarios.

Fig 5. Spatial prediction models of the distributions of habitat suitability for *Prunus africana* under current and future climate scenarios.

Under the current climatic conditions, the less suitable and moderately suitable habitats cover larger areas compared to highly suitable and suitable habitats for both *Pouteria adolfi-friederici* and *Prunus africana* (Fig 6 and 7).

Fig 6. Relative area proportion (%) of suitable habitat categories of *Pouteria adolfi-friederici* under current and future climate scenarios.

Fig 7. Relative area proportion (%) of suitable habitat categories of *Prunus africana* under current and future climate scenarios.

Prediction of habitat suitability under future climate scenarios

The prediction of the distributions of habitat suitability of both study species under future climatic scenarios has shown a similar pattern to the current climate conditions. However, there are variations in terms of the percent of the relative areas across the future climate change scenarios, mainly for the three suitability classes, i.e., less suitable, moderately suitable and suitable habitats (Fig 4 and 5). Unlike these three suitability classes, the relative area of the highly suitable habitats for both tree species does not significantly vary across these scenarios (Fig 6 and 7).

The distribution patterns of habitat suitability in the major vegetation types

(A) *Pouteria adolfi-friederici*

The relative proportion of the distribution of highly suitable habitat is higher under the current climate conditions in MAF when compared with the future climate change scenarios. However, there is a declining trend of this habitat class for this species in MAF under both future climate change scenarios (Fig 8). The proportion of suitable habitats of this species have shown a decreasing trend in all major vegetation types from the current conditions to future climate change scenarios for 2050 and 2070 but their proportions vary among the types (Fig 8). Both ACW and OTHERS (e.g. riverine vegetation) are not favorable for both species.

Fig 8. Relative area proportion (%) of suitable habitats of *Pouteria adolfi-friederici* by major vegetation types under current and future climate scenarios.

(B) *Prunus africana* tree species

The highly suitable habitats of *Prunus africana* tend to decline from the current to under future climate change scenarios in 2050 and 2070 (Fig 9). These habitats class will be useful for this species in CTW until 2050 for RCP 4.5, but it will be fully non-existent in 2070 and for RCP 8.5. There will also be suitable habitats in DAF for *Prunus african* despite DAF will be with less favorable habitats for this species than MAF and OTHERS. But the OTHERS vegetation type, mainly riverine, will have more favorable habitats for this species under both future climate change scenarios for 2050 and 2070 than at the current climate conditions.

Fig 9. Relative area proportion (%) of suitable habitats of *Prunus africana* by major vegetation types under current and future climate scenarios.

The result of the independent t-test indicated that there is significant elevational shift in range of highly suitable habitats for *Prunus africana* between the current and future climate scenarios (Table 3) while similar trend was seen for *Pouteria adolfi-friederici* except under the RCP 4.5 at 2070, which indicated insignificant result. Moreover, the result of the linear model analyses indicated that the topographic position index has significantly affected all the three habitat categories of both study tree species ($P < 0.001$, Table 4 and 5), and is the most influential variable to determine the distribution of potential suitable habitats for *Pouteria adolfi-friederici* and *Prunus africana*.

Table 3: The elevational range shift status of highly suitable habitats between the current and future climate scenarios.

Species	Current	Future	2050	2070	P-values	
	scenario	scenario			2050	2070
<i>Pouteria adolfi-</i>						
<i>friederici</i>	1871.4±246.5	RCP 4.5	1841.45±160.9	1874.9±156.8	0.02	0.78
		RCP 8.5	1934.05±142.7	1911.9±143.1	<0.001	0.003
<i>Prunus.</i>					0.034	<0.001
<i>africana</i>	2248.5±168.4	RCP 4.5	2220.9±199.5	2330.3±187.8		
		RCP 8.5	2291.7±188.6	2346.4±168.1	<0.001	<0.001

Table 4. The linear models (lowest AIC and higher Adjusted R²) of the five habitat suitability categories for *Pouteria adolfi-friederici* under the current, 2050 and 2070 years predicted by three bioclimatic factors generated from the freely accessible Global Bioclim data.

Suitability						
class	Model	Variables	Estimate	Adjusted R ²	AIC	P-values
Highly suitable	Model 1	elev	2.55E-04			0.799
		sri	7.13E-04	0.5198	570658.31	0.841
		tpi	5.01E-03			<0.001
	Model 2	tpi	5.01E-03	0.5199	370654.4	<0.001
Suitable	Model 1	elev	0.004867			0.787
		sri	-0.00594	0.4922	5115330.1	0.926
		tpi	0.085357			<0.001
	Model 2	tpi	0.085363	0.4923	3115326.1	<0.001

Moderately						
suitable	Model 1	elev	0.016043	0.487	5126439.8	0.665
		sri	-0.00581			0.965
		tpi	0.173404			<0.001
	Model 2	tpi	0.173405	0.4871	3126436.0	<0.001
Less suitable	Model 1	elev	0.017498	0.4496	5135544.7	0.793
		sri	-0.09269			0.696
		tpi	0.28994			<0.001
	Model 2	sri	-0.101464	0.4497	4135542.7	0.666
		tpi	0.289922			<0.001
	Model 3	tpi	0.29005	0.4498	3135540.9	<0.001

* elev: elevation, sri: solar radiation index and tpi: topographic position index

Table 5. The linear models (lowest AIC and higher Adjusted R²) of the four habitat suitability categories for *Prunus africana* under current, 2050 and 2070 years predicted by three variables generated from the freely accessible Global Bioclim data.

Suitability						
class	Model	Variables	Estimate	Adjusted R ²	AIC	P-values
Highly suitable	Model 1	elev	1.62E-05			0.97
		sri	-8.36E-04	0.3988	560033.35	0.64
		tpi	1.97E-03			<0.001
	Model 2	tpi	1.97E-03	0.3989	360029.6	<0.001
Suitable	Model 1	elev	0.009257			0.58
		sri	0.008932	0.5137	5114110.8	0.88

		tpi	0.082371			<0.001
	Model 2	tpi	0.082357	0.5138	3114107	<0.001
Moderately						
suitable	Model 1	elev	0.001973			0.96
		sri	-0.102804	0.3898	5126695.4	0.44
		tpi	0.144517			<0.001
	Model 2	tpi	0.144645	0.3899	3126692	<0.001
Less suitable	Model 1	elev	0.004568			0.95
		sri	-0.236376	0.3638	5136732.8	0.36
		tpi	0.261773			<0.001
	Model 2	tpi	0.262068	0.3639	3136730	<0.001

* elev: elevation, sri: solar radiation index and tpi: topographic position index

Discussions

The distributions of the species niches are reciprocally related to the dynamics in environmental variables or climatic variables. Understanding such distributions in potential suitable habitats of indigenous flora is critically important for designing conservation strategies in this era of climate change. To this end, we modeled the distributions of the potential suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* tree species under current and two future climate change scenarios (i.e., RCP 4.5 and RCP 8.5 by 2050 and 2070) and in relation to the major vegetation types of Ethiopia. Here, we show that the potential suitable habitats are predicted to be in the southwest part of Ethiopia in: moist evergreen, dry evergreen forest and grassland complex and *Combretum-Terminalia* woodland vegetation types for *Pouteria adolfi-friederici*, where high moisture is prevalent. Moreover, our prediction model indicated that the distribution of high

suitable habitats may be in the west central parts of Ethiopia in dry evergreen forest and grassland complex and in riverine vegetation types for *Prunus africana* tree species. Interestingly, the prediction models show that the distributions of the suitable habitats or niches of these tree species can shift among the vegetation types or ecosystems due to the effect of the future climate change scenario (Fig 4 and 5). The trend of the distributions of highly suitable habitats of both species *have* shown shifts species under different climate scenarios. In this regard, our results corroborate several previous studies that explained that climate change can affect the adaptive habitat ranges of plant species [2,50,52,59]. From the present study, such range shifts in distributions were manifested by either increasing or decreasing in areas under climate scenarios of 2050 and 2070 (Fig 6 and 7) and this trend was also highlighted with earlier findings [60,61].

Our study has revealed that the environmental factors such as, solar radiation, Precipitation of Warmest Quarter and elevation have significantly mediated the distributions of the potential suitability habitats of the two study species (Table 2) and. For example, Precipitation Seasonality and Precipitation of Driest Quarter are the drivers of the distribution of the suitable habitats of *Pouteria adolfi-friederici* while mean monthly temperature and temperature of coldest quarter are predicted to affect the habitat suitability ranges of *Prunus africana* in Ethiopia.

Understandably, such trends of fluctuations in distributions of suitable habitats may arise from the fact that the plant species have their own specific optimum demands for temperature, precipitation and altitudinal range. In this nexus, [52] from Nepal reported that the temporal variations in temperatures and precipitations are the key factors in fluctuations of the adaptive ranges of plant species. On the other hand, in the tropics, the magnitude of the solar radiation remains a constant input under both current and the future climate scenarios and as a result may

not be accountable for the variations of the distributions of the potential suitable habitats of the different plant species (Table 5). Of course, the significance of the impacts of these environmental factors is related to the elevational gradients. As a result, different plant species may move out of their fundamental niches and occupy the realized ecological zones; yet, if failed to adapt may go extinct under the future climate change scenarios [62,63]. Unequivocally, several previous findings have related that change in climatic conditions alter the distributions of biological species [64–66].

Among the biological characteristics that limit the distributions of the plant species could be their dispersal mechanisms besides the impacts climatic change [2]. Thus, despite the southern parts of the southwest regions and west central areas will be highly suitable habitat potential for *Pouteria adolfi-friederici* and *Prunus africana*, the species may not fully occupy the predicted suitable habitats due to the recalcitrant nature of their seeds, which are sensitive to fluctuation of environmental variables and liable to pest and disease damages [67,68]. Moreover, their seeds may not reach the suitable areas because of limitations of appropriate dispersal agents of the species.

Patterns of distribution of suitable habitats in relation to major vegetation types

The prediction models indicated that, under all the climate scenarios, moist afro-montane, dry afro-montane and *Combretum-Terminalia* woodland vegetation types were found to be highly suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* during the periods of 2050 and 2070 (Fig 8 and 9). Moreover, from other group of vegetation types, the riverine vegetation was identified to be a high suitable habitat of *Prunus africana*, which is most likely favoured by microrefugia habitat moderated by local climate condition (mainly moisture) associated with the

riverine. The highly suitable areas identified for the study species within the *Combretum-Terminalia* woodland vegetation are contributed due to the presence of confined suitable habitats within the *Combretum-Terminalia* Woodland and in the ecotones that moist afro-montane and dry afro-montane vegetation types share with the *Combretum-Terminalia* woodland vegetation type. The highly suitable areas of *Prunus africana* in *Combretum-Terminalia* was identified for RCP 4.5 by 2050 embedded in ecotones in the transition among moist afro-montane, *Combretum-Terminalia* and dry afro-montane vegetation types (Fig 5). However, these habitats seem unfavorable for this species under RCP 8.5 may be due to the impact of high temperature. The spatial distributions of potential suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* tree species showed significant shifts along elevational gradients under the current and the future scenarios (Table 3). Similarly, topographic position was found to be important factor in driving the distributions of the suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* tree species, but such impact was not found for elevation and solar radiation (Table 4 and 5).

In general, in terms of the relative proportions of the areas predicted to be suitable habitats for both tree species, the trend show that the areas are decreasing under future climate scenarios when compared with the current status (Fig 6 and 7). In this connection, our results corroborate the earlier findings that pointed out that the climate change is highly responsible for the area contraction of suitable habitats of the plant [52,69-72]. In general, it is of quite importance to undertake the prediction models of the effects of climate change on the distributions of suitable habitats of floras not only just in terms of area shift but also by ecosystems and biomes. Moreover, the present study is limited only to exploration of the impacts of the bioclimatic variables including solar radiation, elevation and topographic position indices and it may also be

interesting to examine the effects of other factors such as, soil types on the distribution of floras during this changing climate under and future scenarios.

Conclusions

The impacts of climate change and topographic factors are critical to determine the distributions of the suitable habitats for plant species. In this regard, our study denoted that the environmental factors such as, elevation, solar radiation, topographic positions, temperature and precipitation have significantly contributed in the prediction models of the distributions of the potential suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* tree species the under and future climate scenarios (RCP 4.5 and 8.5) of 2050 and 2070 periods. During these periods, the highly suitable habitats of both tree species showed spatial and elevational shifts. For example, there is a shift of highly suitable habitats of *Pouteria adolfi-friederici* from the northern and central parts of the southwest MAF to its southern areas according to the RCPs scenarios. Similarly, the highly suitable habitats of *Prunus africana* was predicted to shift from the western areas of Ethiopia to the west central regions. By sum, from our study, we conclude that the strategies wish to design national biodiversity conservation should take into account dynamics of the suitable niches of different species under changing climate scenarios for the future.

Acknowledgements

Our thanks goes to the Plant Biology and Biodiversity Management for facilitating, and the National Herbarium of Addis Ababa University for permitting us to collect species presence data from the specimens housed in the Herbarium. Finally, we extend our heartfelt thanks to Prof. Sebsebe Demissew and Prof. Ib Friis for permitting us to use the shape file of the Potential Vegetation Types of Atlas of Ethiopia.

Authors contributions

The authors have equal contributions to the study. They s have participated on designing the study, data collection, data analysis and interpretation, discussing the results and drawing conclusions on the findings of the study.

References

1. Bambach N, Meza FJ, Gilabert H, Miranda M. Impacts of climate change on the distribution of species and communities in the Chilean Mediterranean ecosystem. *Reg Environ Change*. 2013;13:1245-1257.
2. Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F. Impacts of climate change on the future of biodiversity. *Ecol Lett*. 2012;15:365-377.
3. Peterson AT, Soberón J. Species distribution modeling and ecological niche modeling: getting the concepts right. *Perspect Ecol Conserv*. 2012; 10:102-107.
4. Boudiaf B, Dabanli I, Boutaghane H, Şen Z. Temperature and precipitation risk assessment under climate change effect in northeast Algeria. *Earth Syst. Environ*. 2020; 1-14. <https://doi.org/10.1007/s41748-019-00136-7>
5. Arnell N, Reynard N. The effects of climate change due to global warming on river flows in Great Britain. *J Hydrol (Amst)*. 1996;183:397-424.
6. Arnell NW. Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: future streamflows in Britain. *J Hydrol (Amst)*. 2003; 270:195-213.
7. Houghton J. Global warming. *Rep Prog Phys*. 2005; 68:1343. Available: <http://iopscience.iop.org/journal/0034-4885>

8. MacKinnon K, Sobrevila C, Hickey V. Biodiversity, climate change, and adaptation: nature-based solutions from the World Bank portfolio. The World Bank, 2008. Available: <http://documents.worldbank.org/curated/en/149141468320661795/Biodiversity-climate-change-and-adaptation-nature-based-solutions-from-the-World-Bank-portfolio>.
9. Houghton J. Global warming: the complete briefing. Cambridge university press; 2009.
10. McCarthy MP, Best MJ, Betts RA. Climate change in cities due to global warming and urban effects. *Geophys Res Lett*. 2010; 37. Doi: [10.1029/2010GL042845](https://doi.org/10.1029/2010GL042845).
11. Lineman M, Do Y, Kim JY, Joo GJ. Talking about climate change and global warming. *PloS one*. 2015; 10:e0138996. Available: <https://doi.org/10.1371/journal.pone.0138996>
12. Bein T, Karagiannidis C, Quintel M. Climate change, global warming, and intensive care. *Intensive Care Med*. 2019; 46:485–487. Available: <https://doi.org/10.1007/s00134-019-05888-4>
13. Hansen J, Sato M, Ruedy R, Lo K, Lea DW, Medina-Elizade M. Global temperature change. 2006; 103:14288-14293. Available: www.pnas.org/cgi/doi/10.1073/pnas.0606291103.
14. New M, Liverman D, Schroder H, Anderson K. Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. The Royal Society Publishing; 2011.
15. Huntingford C, Jones PD, Livina VN, Lenton TM, Cox PM. No increase in global temperature variability despite changing regional patterns. *Nature*. 2013; 500:327-330.
16. Rastogi M, Singh S, Pathak H. Emission of carbon dioxide from soil. *Curr Sci*. 2002; 82:510-517. Available: <https://www.jstor.org/stable/24105957>

- 426 17. Solomon S, Plattner GK, Knutti R, Friedlingstein P. Irreversible climate change due to
427 carbon dioxide emissions. PNAS.2009; 106:1704-1709. Available:
428 <https://doi.org/10.1073/pnas.081272110>
- 429 18. Kajaste R., Hurme M. Cement industry greenhouse gas emissions–management options and
430 abatement cost. J Clean Prod. 2016; 112:4041-4052.
- 431 19. Pachauri RK, Reisinger A. IPCC fourth assessment report. *IPCC, Geneva*; 2007.
- 432 20. Woodward A, Smith KR, Campbell-Lendrum D, Chadee DD, Honda Y, Liu Q, et al. Climate
433 change and health: on the latest IPCC report. The Lancet. 2014; 383:1185-1189.
- 434 21. Hannah L, Midgley G, Lovejoy T, Bond W, Bush M, Lovett J, et al. Conservation of
435 biodiversity in a changing climate. Conserv Biol. 2002; 16:264-268.
- 436 22. Kannan R, James. Effects of climate change on global biodiversity: a review of key
437 literature. Trop Ecol. 2009; 50:31.
- 438 23. Scarano FR. Biodiversity sector: risks of temperature increase to biodiversity and
439 ecosystems, Climate change risks in Brazil. Springer. 2019; 131-141. DoiI: [10.1007/978-](https://doi.org/10.1007/978-3-319-92881-4_5)
440 [3-319-92881-4_5](https://doi.org/10.1007/978-3-319-92881-4_5)
- 441 24. Lovejoy TE. Climate change and biodiversity. ISBN 81-7993–084-X; 2006. Available:
442 <https://citeseerx.ist.psu.edu>
- 443 25. García FC, Bestion E, Warfield R, Yvon-Durocher G. Changes in temperature alter the
444 relationship between biodiversity and ecosystem functioning. PNAS. 2018; 115:10989-
445 10994.
- 446 26. Parain EC, Rohr RP, Gray SM, Bersier L.F. Increased temperature disrupts the biodiversity–
447 ecosystem functioning relationship. Am Nat. 2019; 193:227-239.

27. Perrings C. Biodiversity, ecosystem services, and climate change. The Economic Problem/Environment department papers. 2010; 120:1-39. Available: <https://openknowledge.worldbank.org>.
28. Rinawati F, Stein K, Lindner A. Climate change impacts on biodiversity—the setting of a lingering global crisis. *Divers*. 2013; 5:114-123.
29. Louthan AM, Doak DF, Angert AL. Where and when do species interactions set range limits? *Trends Ecol Evol*. 2015; 30:780-792.
30. Hedberg I, Edwards S. Flora of Ethiopia: Pittosporaceae to Araliaceae: the National Herbarium. Uppsala: Addis Ababa, Ethiopia, and Department of Systematic Botany; 1989; 3.
31. Hedberg I, Edwards S, Nemomissa S. Flora of Ethiopia and Eritrea: Apiaceae to Dipsacaceae. Addis Ababa, Ethiopia and Uppsala, Sweden: The National Herbarium, Addis Ababa University; 2003; 4: 1.
32. Friis I, Demissew S, van Breugel P. Atlas of the potential vegetation of Ethiopia. Det Kongelige Danske Videnskabernes Selskab; 2010.
33. Negash L. Indigenous trees of Ethiopia. Biology, uses and propagation techniques. SLU Reprocentralen, Umeå, Sweden; 1995.
34. Bekele T, Berhan G, Taye E, Ersado M, Yeshitela K. Regeneration status of moist Montane forest of Ethiopia: Consideration for Conservation part. *Walia*. 2001:45-62. Available: <https://www.researchgate.net/publication/313988325>
35. Lemenih M, Teketay D. Restoration of native forest flora in the degraded highlands of Ethiopia: constraints and opportunities. *SINET*. 2004; 27:75-90.

36. Cunningham A, Anoncho V, Sunderland T. Power, policy and the *Prunus africana* bark trade, 1972–2015. J Ethnopharmacol. 2016; 178:323-333.
37. Stewart KM. The African cherry (*Prunus africana*): can lessons be learned from an over-exploited medicinal tree? J Ethnopharmacol. 2003 Nov;89(1):3-13. doi: 10.1016/j.jep.2003.08.002. PMID: 14522426.
38. World Conservation Monitoring Centre. 1998. *Prunus africana*. The IUCN Red List of Threatened. e.T33631A9799059; 1998. Available: <https://dx.doi.org/10.2305/IUCN.UK.1998.RLTS.T33631A9799059.en>.
39. Kadu CA, Parich A, Schueler S, Konrad H, Muluvi GM, Eyog-Matig O, et al. Bioactive constituents in *Prunus africana*: geographical variation throughout Africa and associations with environmental and genetic parameters. Phytochemistry. 2012; 83:70-78.
40. Lompo D, Vinceti B, Konrad H, Gaisberger H, Geburek T. Phylogeography of African locust bean (*Parkia biglobosa*) reveals genetic divergence and spatially structured populations in West and Central Africa. J Hered. 2018; 109:811-824.
41. McCann JC. The plow and the forest: narratives of deforestation in Ethiopia, 1840-1992. Environ Hist Durh N C. 1997; 2:138-159.
42. Getahun K, Rompaey AV, Turnhout PV, Joesen J. Factors controlling patterns of deforestation in moist evergreen Afromontane forests of Southwest Ethiopia. For Ecol Manage. 2013; 304: 171-181.
43. Guillozet K, Bliss JC, Kelecha TS. Degradation in an Afromontane forest in highland Ethiopia, 1969–2010. Small-Scale For. 2015; 14:121-137.

44. EFCCC. Ethiopia's Forest Reference Level Submission to the UNFCCC. 2017; 1-77.
Available: <http://redd.unfccc.int> › files › ethiopia_frel_3.2_fi...
45. Diffenbaugh NS, Giorgi F. Climate change hotspots in the CMIP5 global climate model ensemble. *Clim Change*. 2012; 114:813-822.
46. He C, Zhou T. Responses of the western North Pacific subtropical high to global warming under RCP4. 5 and RCP8. 5 scenarios projected by 33 CMIP5 models: The dominance of tropical Indian Ocean–tropical western Pacific SST gradient. *J Clim*. 2015; 28:365-380.
47. Brown SC, Wigley TM, Otto-Bliesner BL, Rahbek C, Fordham DA. Persistent Quaternary climate refugia are hospices for biodiversity in the Anthropocene. *Nat Clim Chang*. 2020; 10:244-248.
48. Reisinger A, Meinshausen M, Manning M. Future changes in global warming potentials under representative concentration pathways. 2011; Doi: 10.1088/1748-9326/6/2/024020.
49. Brown JL. SDMtoolbox: a python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. *Methods in Ecology and Evolution*. *Methods Ecol Evol*. 2014; 5: 694–700. Doi: 10.1111/2041-210X.12200.
50. Barbosa FG, Pillar VD, Palmer AR, Melo AS. Predicting the current distribution and potential spread of the exotic grass *Eragrostis plana* Nees in South America and identifying a bioclimatic niche shift during invasion. *Austral Ecol*. 2013; 38:260-267.
51. Vega GC, Pertierra LR, Olalla-Tárraga MÁ. MERRAclim, a high-resolution global dataset of remotely sensed bioclimatic variables for ecological modelling. *Sci Data*. 2017; 4:1-12.
52. Chhetri PK, Gaddis KD, Cairns DM. Predicting the suitable habitat of treeline species in the Nepalese Himalayas under climate change. *Mt Res Dev*. 2018; 38:153-163.

53. Ma B, Sun J. Predicting the distribution of *Stipa purpurea* across the Tibetan Plateau via the MaxEnt model. *BMC Ecol.* 2018; 18: 1-12.
54. Phillips SJ, Anderson RP, Schapire RE. Maximum entropy modeling of species geographic distributions. *Ecol Modell.* 2006; 190:231-259.
55. Fan J, Upadhye S, Worster A. Understanding receiver operating characteristic (ROC) curves. *CJEM.* 2006; **8**:19-20.
56. Fourcade Y, Engler JO, Rödder D, Secondi J. Mapping species distributions with MaxEnt using a geographically biased sample of presence data: a performance assessment of methods for correcting sampling bias. *PloS one* 9:e97122. 2014; 9: <https://doi.org/10.1371/journal.pone.0097122>
57. Araújo MB, Pearson RG, Thuiller W, Erhard M. Validation of species–climate impact models under climate change. *Glob Chang Biol.* 2005; 11:1504-1513.
58. R Foundation for Statistical Computing, Vienna, Austria; 2021. Available: URL <http://www.R-project.org/>.
59. Stalin N, Swamy P. Prediction of suitable habitats for *Syzygium caryophyllatum*, an endangered medicinal tree by using species distribution modelling for conservation planning. *Eur J Exp Biol.* 2015; 5:12-19.
60. Buckley LB, Urban MC, Angilletta MJ, Crozier LG, Rissler LJ, Sears MW. Can mechanism inform species' distribution models? *Ecol Lett.* 2010; 13:1041-1054.
61. Shirk AJ, Cushman SA, Waring KM, Wehenkel CA, Leal-Sáenz A, Toney C, et al. Southwestern white pine (*Pinus strobiformis*) species distribution models project a large range shift and contraction due to regional climatic changes. *For Ecol Manage.* 2018; 411:176-186.

62. Provan J, Maggs CA. Unique genetic variation at a species' rear edge is under threat from global climate change. *Proc R Soc Lond B Biol Sci.* 2012; 279:39-47.
63. Zhang K, Zhang Y, Zhou C, Meng J, Sun J, Zhou T, et al. Impact of climate factors on future distributions of *Paeonia ostii* across China estimated by MaxEnt. *Ecol Inform.* 2019; 50:62-67.
64. Zhu K, Woodall CW, Clark JS. Failure to migrate: lack of tree range expansion in response to climate change. *Glob Chang Biol.* 2012; 18:1042-1052
65. Gül S, Kumlutaş Y, Ilgaz C. Potential distribution under different climatic scenarios of climate change of the vulnerable Caucasian salamander (*Mertensiella caucasica*): A case study of the Caucasus Hotspot. *Biol Futur.* 2018; 73:175-184.
66. Wei B, Wang R, Hou K, Wang X, Wu W. Predicting the current and future cultivation regions of *Carthamus tinctorius* L. using MaxEnt model under climate change in China. *Glob Ecol Conserv.* 2018; 16:e00477.
67. Albrecht J. Tree Seed Handbook of Kenya. Kenyan Forestry Research Institute and GTZ Forestry Seed Centre Muguga, Nairobi; 1993.
68. Lemmens RH. *Pouteria adolfi-friedericii* (Engl.) A.Meeuse. In: Louppe, D., Oteng-Amoako, A.A. & Brink, M. (Editors). PROTA (Plant Resources of Tropical Africa / Ressources végétales de l'Afrique tropicale), Wageningen, Netherlands; 2007.
69. Hampe A, Petit RJ. Conserving biodiversity under climate change: the rear edge matters. *Ecol Lett.* 2005; 8:461-467.
70. Bridle JR, Vines TH. Limits to evolution at range margins: when and why does adaptation fail? *Trends Ecol Evol.* 2007; 22:140-147.

71. Cobos ME, Peterson AT, Barve N, Osorio-Olvera L. kuenm: an R package for detailed development of ecological niche models using Maxent. PeerJ. 2019; 7:e6281.
72. Gao T, Xu Q, Liu Y, Zhao J, Shi J. Predicting the Potential Geographic Distribution of *Sirex nitobei* in China under Climate Change Using Maximum Entropy Model. Forests. 2012; 12:151.

Figures Cations

Fig 2. The current occurrences of *Pouteria adolfi-friederici* and *Prunus africana* tree species across five major vegetation types of Ethiopia.

Fig 2. Response curves of four top contributing variables to distribution of *P. adolfi-friederici*: solar radiation, Precipitation of Warmest Quarter, Precipitation of Driest Quarter and Precipitation Seasonality.

Fig 3. Response curves of four top contributing variables to distribution of *Prunus africana*: solar radiation, mean temperature of coldest quarter, precipitation of warmest quarter and elevation.

Fig 4. Spatial prediction models of the distributions of habitat suitability for *Pouteria adolfi-friederici* under current and future climate scenarios.

Fig 5. Spatial prediction models of the distributions of habitat suitability for *Prunus africana* under current and future climate scenarios.

Fig 6. Relative area proportion (%) of suitable habitat categories of *Pouteria adolfi-friederici* under current and future climate scenarios.

Fig 7. Relative area proportion (%) of suitable habitat categories of *Prunus africana* under current and future climate scenarios.

Fig 8. Relative area proportion (%) of suitable habitats of *Pouteria adolfi-friederici* by major vegetation types under current and future climate scenarios.

Fig 9. Relative area proportion (%) of suitable habitats of *Prunus africana* by major vegetation types under current and future climate scenarios.

Supporting Information

S1 Table. Correlation matrix among 19 current bioclimatic variables, elevation, solar radiation and topographic position indices (done using SDM_v2.4_AcrMap 10.5).

Short title: Distributions of tree species under climate changes

Predicting the distributions of *Pouteria adolfi-friederici* and *Prunus africana* iconic tree species under current and future climate change scenarios in Ethiopia

Zerihun Tadesse^{1,2*}, Sileshi Nemomissa¹, Debissa Lemessa¹

¹Department of Plant Biology and Biodiversity Management, College of Natural and Computational Sciences, Addis Ababa University, Ethiopia

²Department of Plant Science, College of Agriculture, Wollega University, Ethiopia

*Corresponding author: Email: zerihunbio@gmail.com, Mobile phone: 0911080458.

Abstract

The distributions of the potential adaptive ranges of iconic plant species are not yet fully known especially in regions such as Ethiopia where high climatic variability and vegetation types are found. This study was undertaken to predict the distributions of the potential suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* tree species under the current and two future climate scenarios (i.e., RCP 4.5 and RCP 8.5 in 2050 and 2070) using MaxEnt software (version: 3.4.4.). Eleven less correlated environmental variables ($r < 0.7$) were identified and used to make the prediction models. Elevational shifts of the highly suitable habitats, effects of elevation, solar radiation and topographic position in relation to the current and future climatic scenarios on the habitats were statistically analyzed using independent t-test and linear model. Under all climate scenarios, we found a decrease in the proportion of areas of highly suitable habitats for both study species. High potentials of suitable habitats for *Pouteria adolfi-friederici* are predicted to be confined to southwest, west central and south parts of Ethiopia in fragmented moist afro-montane forest patches, while it is in the southwest and west central parts of Ethiopia for *Prunus africana*. On basis of vegetation types of the country, potential suitable habitats for *Pouteria adolfi-friederici* are predicted to occur in moist evergreen forest, dry evergreen forest and grassland complex and *Combretum-Terminalia* woodland vegetation types. Whereas, moist evergreen forest, dry evergreen forest and grassland complex and riverine vegetation types are predicted to comprise potential suitable habitats for *Prunus africana*, showing considerable spatial dynamics. Overall, our results suggest that the strategies deem to design biodiversity conservation should take into account the dynamics of the suitable niches of different species under different future climate scenarios.

Keywords: adaptive range, climate change, Ethiopia, prediction model, habitat suitability, range shift, species distribution.

Introduction

Plant species have their optimum range of climatic condition to survive in their ecological zones [1]. Among others, the environmental factors limiting the adaptive range of the plant species are altitude, temperature, moisture, and soil types [2,3]. Climate, which represents a weather condition over a wide environment for a long period, plays important role to determine the distribution of plant species in their suitable ecological regions [2]. Temperature and precipitation are the most important environmental variables determining the climatic condition of ecological regions to which plant species are naturally adapted to grow [4]. Temperature and moisture can change as a result of climate change and challenge populations of a species already well adapted to the climatic conditions of ecological regions for long period [3]. However, different studies are depicting that climate change is taking place over the world due to global warming [5-12]. Climate change is mainly caused by increasing global temperature [13-15] that is initiated mainly due to greenhouse gas (GHG) emissions from multiple sources [16-18]. Thus, a change in global temperature and precipitation [19,20] can affect the distribution of global biodiversity in the future [21-23]. Plants can change their range of distribution to respond to the climate change [24-26] and either go extinct [27] or there would be shifting out from of their current ecological niches to new ecological areas [28,29].

Pouteria adolfi-friederici and *Prunus africana* tree species, which belong to Sapotaceae and Rosaceae families respectively, are iconic trees occurring in remnant fragments of moist and dry afro-montane forests. The species are currently existing in scattered patterns with limited number in some agricultural landscapes of Ethiopia [30-32]. *Pouteria adolfi-friederici* is a timber tree

that can grow up to 50 m, having a clear straight bole usually reaching over 16 m height with narrow conical canopy in moist afro-montane forests within altitudinal range of 1350–2450m a.s.l in Ethiopia [31]. Its seeds are recalcitrant and sensitive to desiccation and need to be sown while they are in fresh condition [33-35] and effective germination thereof demands optimum temperature and moisture.

The other iconic tree species that has overlapping niche with *Pouteria adolfi-friederici* is *Prunus africana*. *Prunus africana*, the African cherry, is a valuable timber tree growing up to 40 m high with a diameter of 1m in moist and dry afro-montane forests [33]. Similar to *Pouteria adolfi-friederici*, seeds of *Prunus africana* are recalcitrant and lose viability in a short period of time when exposed to low moisture condition. The bark extract of this species is used to treat benign prostatic hyperplasia and has drawn a considerable commercial interest [36]. Therefore, these two indigenous tree species, *Pouteria adolfi-friederici* and *Prunus africana*, were selected in our study mainly for three fundamental reasons: firstly, their seeds cannot be conserved in low temperature or in cold gene bank and, thus, they can only be conserved at their natural habitats or niches; secondly, the species have remarkable ecological and economic significance; and thirdly, *Prunus africana* is assessed as vulnerable [37,38] and the populations of both species are under extensive overexploitations for various uses. Moreover, previous studies have focused on phylogeography and medicinal uses of *Prunus africana* [36,39,40] and only limited study was conducted on *Pouteria adolfi-friederici*. Afro-montane forests of Ethiopia where these iconic tree species are mainly confined to have been under immense threat due to deforestation problem [41-43]. The deforestation has resulted in diminishing of suitable habitats of these important tree species although their potential distributions in Ethiopia under climate change is not yet well known. Thus, studying the potential suitable habitat distributions of the species could have

informed decisions for their conservation interventions. Therefore, the aim of this study was to understand the distributions of *Pouteria adolfi-friederici* and *Prunus africanatree* species under the current climatic condition and predict their potential suitable habitats using two climate change scenarios (RCP 4.5 and RCP 8.5 in 2050 and 2070). Here, we hypothesized that, (1), there are unoccupied suitable niches under the current climatic condition for both species in ecosystems where previously no geographical detections were addressed, (2) there will be range shifts in distributions of potential suitable habitats for both species in the future beyond the moist and dry afro-montane forest ecosystems, emanating from the changes in climatic conditions.

Materials and Methods

Study system

The study was undertaken within the geographical area of Ethiopia, which lies between 3°24' – 14° 53' N and 32° 42' – 48°12' E (Fig 1). The total area of Ethiopia is 1.13×10^6 square km and this is approximately equal to 113,289,457 ha within the elevational range of 124 m b.s.l. to 4560 m a.s.l.

Fig 3. The current occurrences of *Pouteria adolfi-friederici* and *Prunus africanatree* species across five major vegetation types of Ethiopia.

Historically, the vegetation of Ethiopia has been classified in several ways, but, recently [32] has classified into 12 potential vegetation types. In the study of [44], these 12 potential vegetation types have been classified into 5 major vegetation groups (Fig 1 and Table 1) for conservation purposes, and we have used them for this study.

Table 1: Five major vegetation groups from the 12 potential vegetation types of Ethiopia

Grouped 5 major vegetation types	Vegetation types as classified in the study [32]
----------------------------------	--

<i>Acacia-Commiphora</i> woodland	<i>Acacia-Commiphora</i> woodland and bushland (ACB); Acacia wooded grassland (ACB); Desert and semi-desert scrubland (DSS)
<i>Combretum-Terminalia</i> woodland	<i>Combretum-Terminalia</i> woodland and wooded grassland (CTW); Wooded grassland of the Western Gambela region (WGG)
Dry Afromontane Forest (DAF)	Dry evergreen Afromontane Forest and Grassland complex (DAF) Afro-Alpine vegetation (AA); and Ericaceous Belt (EB);
Moist Afromontane Forest (MAF)	Moist Evergreen Afromontane Forest (MAF); Transitional Rain Forest (TRF)
Others	Salt Pans, Saline/brackish and Intermittent wetlands and Salt-lake Shore Vegetation (SLV/SSS); Salt Lake open water vegetation (SLV/OW); Freshwater marshes and swamps, Floodplains and Lake Shore vegetation (FLV/MFS); Freshwater lakes - open water vegetation (FLV/OW)

Method

The species occurrences data of both species were collected from the National Herbarium of Ethiopia and from GBIF (www.gbif.org). Moreover, geographical coordinates of species presence locations were collected using a handheld Garmin GPS in west central areas of the country

during a field work. In total, 94 coordinates (i.e., 30 for *Pouteria adolfi-friederici* and 64 for *Prunus africana*) points were used in this study.

As the current input data, the 19 bioclimatic variables (1970-2000) with a spatial resolution of about 1 km² were downloaded from www.worldclim.org/data/worldclim21.html. Furthermore, solar radiation index (sri) was downloaded from www.worldclim.org/data/worldclim21.html while indices of topographic position and elevation data were downloaded from <https://www.earthenv.org/topography>.

The input data for future climate scenarios of the Coupled Model Inter-comparison Project phase (CMIP5) was used as stated in the studies [45,46]. Here, the downscaled data of Representative Pathways with intermediate (RCP 4.5) and highest concentrations (RCP 8.5) of two periods (2050 and 2070) were downloaded from http://www.worldclim.com/CMIP5_30s. These trajectories are based on their radiative forces (w/m²) and are expected to change at the turn of the century [47,48].

Data analysis

Environmental variables were clipped into Ethiopian boundary shape file using ArcGIS (version: 10.5) and converted into ASCII format using SDMTtoolbox 2.4 [49]. The multicollinearity (i.e., the unnecessary correlation among the predictor variables) was checked for the current data of 19 bioclimatic variables using the pairwise correlation matrix with Pearson correlation analysis (S1 Table). Eleven variables that are less correlated ($r < 0.7$) were included in prediction models and this cut-off point was commonly applied to fit models to bioclimatic data [50-52]. The 11 bioclimatic variables used in the prediction models are mean monthly temperature, isothermality, temperature seasonality, mean temperature of coldest quarter, precipitation seasonality,

precipitation of driest quarter, precipitation of warmest quarter, precipitation of coldest quarter, elevation, solar radiation index and topographic position index.

The species distribution modelling was run with MaxEnt software (version: v.3.4.4., R Core Team, 2021). The modelling was performed with a random test percentage at 25%, regularization multiplier 1, maximum background points of 10,000, maximum iterations at 5000, convergence threshold held at 0.00001 and 10 replicates with averaged results. The model was evaluated by calculating the AUC of ROC graph [53-56]. Concerned average value of AUC graph < 0.7 is bad, $0.7-0.8$ is good and $0.9-1$ is excellent for the species distribution modelling as explained in the study [57].

To analyze habitat suitability, the output maps of 10 replicate runs (0.0–1.0 categories) were used in ArcGIS. Accordingly, five habitat suitability classes were identified as highly suitable (0.85–1.00), suitable (0.69– <0.85), moderately suitable (0.54– <0.69), less suitable (0.38– <0.54) and unsuitable (0.0– <0.38), based on range values of band categories. The area extents were computed in hectare (ha) from the number of pixels counts for each suitable habitat classes. The change in the proportion of the habitats under current and future climate change scenarios (RCP 4.5 and RCP 8.5) was analyzed by overlying MaxEnt output maps over the shape files of the vegetation classes of Ethiopia. Predicted geographic areas in Ethiopia were extracted from Ethiogis database and the area of each was calculated using ArcGIS (version: 10.5).

Model performance evaluation

The model outputs for both *Pouteria adolfi-friederici* and *Prunus africanatree* species indicated that all the test omission rates averaged over ten replicate runs were close to the predicted omission on the training and test rates under the current and future conditions. The average AUC for *Pouteria adolfi-friederici* showed great model fit under the current (0.926), RCP 4.5 (0.911,

0.903) and RCP 8.5 (0.901, 0.910) scenarios, at 2050 and 2070. Average AUC for *Prunus africana* also indicated very good model fit under the current (0.887), RCP 4.5 (0.868, 0.880) and RCP 8.5 (0.885, 0.896) scenarios, at the 2050 and 2070.

The differences in elevational shifts of the habitat suitability categories under current and future climatic scenarios were tested using independent t-test as implemented in R version: 4.1.0. [58]. Moreover, three environmental variables, namely, elevation, solar radiation index and topographic position index, the values of which do not vary across the climatic scenarios, were used to statistically analyze their effect on the different categories of habitat suitability using linear model in R.

Results

Habitat suitability mapping and modelling

The environmental variables significantly contributing to the distributions of habitat suitability of *Pouteria adolfi-friederici* were solar radiation, precipitation of warmest quarter, precipitation of driest quarter, precipitation seasonality, mean temperature of coldest quarter and elevation. Similarly, solar radiation, precipitation of warmest quarter, mean temperature of coldest quarter and mean monthly temperature significantly contribute to determine the distribution of *Prunus africana* under the current (1970–2000) and future (2050 and 2070) climate scenarios (Table 2).

Table 2: The contributions of environmental variables (%) in spatial prediction models of suitable habitats under the current and future climate scenarios of 2050 and 2070 periods.

Variable	<i>Pouteria adolfi-friederici</i>			<i>Prunus africana</i>		
	Current	RCP 4.5	RCP 8.5	Current	RCP 4.5	RCP 8.5

	climate	2050	2070	2050	2070	climate	2050	2070	2050	2070
sri	51.2	39.1	50.8	46.7	51.1	64	57.5	62.1	63.5	58.5
Bio_18	16.3	13.8	16	11.7	10.2	6	10.6	10.1	5.7	4.5
Bio_15	10.5	13.3	8.2	7.8	8.5	0.2	0.1	0.3	0.2	0.1
Bio_11	7.4	1.9	3.8	3.6	4	12.4	9.6	10.5	12.6	13
elev	5.5	1.2	1.5	1.5	2.1	4.7	3.3	3.2	3.3	3.3
Bio_04	3.1	2.9	2	0.7	0.6	0.7	0.5	0.4	0.7	0.3
Bio_19	2.8	2.4	2.5	1.7	3.3	3	5.6	3.3	1.8	7.5
Bio_02	1.5	8.5	6.3	5.8	5.2	1.4	10.5	7.1	9.8	10.2
Bio_17	1.2	13.8	6.7	17.7	12.4	1.1	0.6	1.2	0.8	0.7
tpi	0.3	0.4	0.2	0.1	0.4	0.4	1.3	0.5	0.4	0.4
Bio_03	0.1	2.7	2	2.7	2.2	6.2	0.4	1.4	1.1	1.6

*elev: elevation, sri: solar radiation index, tpi: topographic position index.

Response curves are good informative and indicators for environmental variables contributing to the high probability of the occurrence of habitat suitability for species. The occurrence of highly suitable habitats of *Pouteria adolfi-friederici* was predicted in the range of 15,400–16,200 nm solar radiation, 30–50 mm of precipitation seasonality, 170–250 mm precipitation of driest quarter and 500–700 mm precipitation of warmest quarter (Fig 2).

Fig 2. Response curves of four top contributing variables to distribution of *P. adolfi-friederici*: solar radiation, precipitation of warmest quarter, precipitation of driest quarter and precipitation seasonality.

Similarly, highly suitable habitat for the distribution of *Prunus africana* was predicted between 15,400–16,200 nm of solar radiation, 7.5–15.5°C mean temperature of coldest quarter, 400–700 mm precipitation of warmest quarter and elevation in 2250–2700 m a.s.l. (Fig 3).

Fig 3. Response curves of four top contributing variables to distribution of *Prunus africana*: solar radiation, mean temperature of coldest quarter, precipitation of warmest quarter and elevation.

Habitat suitability mapping under the current climate conditions (1970–2000)

Five habitat suitability classes were identified, i.e., highly suitable, suitable, moderately suitable, less suitable and unsuitable with different area proportions mapped for the two study species. Both moderately and less suitable habitats are areas with unfavorable conditions for both species under the current climate conditions. The distributions of highly suitable and suitable habitats of *Pouteria adolfi-friederici* are largely concentrated in southwest and with a relatively smaller amount in the southeastern part of Ethiopia (Fig 4). For *Prunus africana*, highly suitable and suitable habitats cover most of the central, eastern and western highlands of Ethiopia (Fig 5).

Fig 4. Spatial prediction models of the distributions of habitat suitability for *Pouteria adolfi-friederici* under current and future climate scenarios.

Fig 5. Spatial prediction models of the distributions of habitat suitability for *Prunus africana* under current and future climate scenarios.

Under the current climatic conditions, the less suitable and moderately suitable habitats cover larger areas compared to highly suitable and suitable habitats for both *Pouteria adolfi-friederici* and *Prunus africana* (Fig 6 and 7).

Fig 6. Relative area proportion (%) of suitable habitat categories of *Pouteria adolfi-friederici* under current and future climate scenarios.

Fig 7. Relative area proportion (%) of suitable habitat categories of *Prunus africana* under current and future climate scenarios.

Prediction of habitat suitability under future climate scenarios

The prediction of the distributions of habitat suitability of both study species under future climatic scenarios has shown a similar pattern to the current climate conditions. However, there are variations in terms of the percent of the relative areas across the future climate change scenarios, mainly for the three suitability classes, i.e., less suitable, moderately suitable and suitable habitats (Fig 4 and 5). Unlike these three suitability classes, the relative area of the highly suitable habitats for both tree species does not significantly vary across these scenarios (Fig 6 and 7).

The distribution patterns of habitat suitability in the major vegetation types
(A) *Pouteria adolfi-friederici*

The relative proportion of the distribution of highly suitable habitat is higher under the current climate conditions in MAF when compared with the future climate change scenarios. However, there is a declining trend of this habitat class for this species in MAF under both future climate

change scenarios (Fig 8). The proportion of suitable habitats of this species have shown a decreasing trend in all major vegetation types from the current conditions to future climate change scenarios for 2050 and 2070 but their proportions vary among the types (Fig 8). Both ACW and OTHERS (e.g. riverine vegetation) are not favorable for both species.

Fig 8. Relative area proportion (%) of suitable habitats of *Pouteria adolfi-friederici* by major vegetation types under current and future climate scenarios.

(B) *Prunus africana* tree species

The highly suitable habitats of *Prunus africana* tend to decline from the current to under future climate change scenarios in 2050 and 2070 (Fig 9). These habitats class will be useful for this species in CTW until 2050 for RCP 4.5, but it will be fully non-existent in 2070 and for RCP 8.5. There will also be suitable habitats in DAF for *Prunus african* despite DAF will be with less favorable habitats for this species than MAF and OTHERS. But the OTHERS vegetation type, mainly riverine, will have more favorable habitats for this species under both future climate change scenarios for 2050 and 2070 than at the current climate conditions.

Fig 9. Relative area proportion (%) of suitable habitats of *Prunus africana* by major vegetation types under current and future climate scenarios.

The result of the independent t-test indicated that there is significant elevational shift in range of highly suitable habitats for *Prunus africana* between the current and future climate scenarios (Table 3) while similar trend was seen for *Pouteria adolfi-friederici* except under the RCP 4.5 at 2070, which indicated insignificant result. Moreover, the result of the linear model analyses indicated that the topographic position index has significantly affected all the three habitat categories of both study tree species ($P < 0.001$, Table 4 and 5), and is the most influential

variable to determine the distribution of potential suitable habitats for *Pouteria adolfi-friederici* and *Prunus africana*.

Table 3: The elevational range shift status of highly suitable habitats between the current and future climate scenarios.

Species	Current	Future	2050	2070	P-values	
	scenario	scenario			2050	2070
<i>Pouteria adolfi-friederici</i>						
	1871.4±246.5	RCP 4.5	1841.45±160.9	1874.9±156.8	0.02	0.78
		RCP 8.5	1934.05±142.7	1911.9±143.1	<0.001	0.003
<i>Prunus africana</i>						
	2248.5±168.4	RCP 4.5	2220.9±199.5	2330.3±187.8	0.034	<0.001
		RCP 8.5	2291.7±188.6	2346.4±168.1	<0.001	<0.001

Table 4. The linear models (lowest AIC and higher Adjusted R²) of the five habitat suitability categories for *Pouteria adolfi-friederici* under the current, 2050 and 2070 years predicted by three bioclimatic factors generated from the freely accessible Global Bioclim data.

Suitability						
class	Model	Variables	Estimate	Adjusted R ²	AIC	P-values
Highly suitable	Model 1	elv	2.55E-04			0.799
		sri	7.13E-04	0.5198	570658.31	0.841
		tpi	5.01E-03			<0.001
	Model 2	tpi	5.01E-03	0.5199	370654.4	<0.001
Suitable	Model 1	elv	0.004867			0.787
		sri	-0.00594	0.4922	5115330.1	0.926

		tpi	0.085357			<0.001
	Model 2	tpi	0.085363	0.4923	3115326.1	<0.001
Moderately						
suitable	Model 1	elv	0.016043	0.487	5126439.8	0.665
		sri	-0.00581			0.965
		tpi	0.173404			<0.001
	Model 2	tpi	0.173405	0.4871	3126436.0	<0.001
Less suitable	Model 1	elv	0.017498	0.4496	5135544.7	0.793
		sri	-0.09269			0.696
		tpi	0.28994			<0.001
	Model 2	sri	-0.101464	0.4497	4135542.7	0.666
		tpi	0.289922			<0.001
	Model 3	tpi	0.29005	0.4498	3135540.9	<0.001

* elv: elevation, sri: solar radiation index and tpi: topographic position index

Table 5. The linear models (lowest AIC and higher Adjusted R²) of the four habitat suitability categories for *Prunus africana* under current, 2050 and 2070 years predicted by three variables generated from the freely accessible Global Bioclim data.

Suitability						
class	Model	Variables	Estimate	Adjusted R ²	AIC	P-values
Highly suitable	Model 1	elv	1.62E-05			0.97
		sri	-8.36E-04	0.3988	560033.35	0.64
		tpi	1.97E-03			<0.001
	Model 2	tpi	1.97E-03	0.3989	360029.6	<0.001

Suitable	Model 1	elv	0.009257			0.58
		sri	0.008932	0.5137	5114110.8	0.88
		tpi	0.082371			<0.001
	Model 2	tpi	0.082357	0.5138	3114107	<0.001
Moderately						
suitable	Model 1	elv	0.001973			0.96
		sri	-0.102804	0.3898	5126695.4	0.44
		tpi	0.144517			<0.001
	Model 2	tpi	0.144645	0.3899	3126692	<0.001
Less suitable	Model 1	elv	0.004568			0.95
		sri	-0.236376	0.3638	5136732.8	0.36
		tpi	0.261773			<0.001
	Model 2	tpi	0.262068	0.3639	3136730	<0.001

* elv: elevation, sri: solar radiation index and tpi: topographic position index

Discussions

The distributions of the species niches are reciprocally related to the dynamics in environmental variables or climatic variables. Understanding such distributions in potential suitable habitats of indigenous flora is critically important for designing conservation strategies in this era of climate change. To this end, we modeled the distributions of the potential suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* tree species under current and two future climate change scenarios (i.e., RCP 4.5 and RCP 8.5 by 2050 and 2070) and in relation to the major vegetation types of Ethiopia. Here, we show that the potential suitable habitats are predicted to be in the southwest parts of Ethiopia in: moist evergreen, dry evergreen forest and grassland complex and

Combretum-Terminalia woodland vegetation types for *Pouteria adolfi-friederici*, where high moisture is prevalent. Moreover, our prediction model indicated that the distribution of high suitable habitats may be in the west central parts of Ethiopia in dry evergreen forest and grassland complex and in riverine vegetation types for *Prunus africana* tree species. Interestingly, the prediction models show that the distributions of the suitable habitats or niches of these tree species can shift among the vegetation types or ecosystems due to the effect of the future climate change scenario (Fig 4 and 5), which can be understood from the trend of range shifting took place by the highly suitable habitats for both study species. In this regard, our results corroborate several previous studies that explained as climate change can affect the adaptive habitat ranges of plant species across their natural ecosystems [2,50,52,59]. From the present study, such habitat range shift distributions were manifested by either increasing or decreasing in areas under the climate scenarios of 2050 and 2070 (Fig 6 and 7) and this trend was also highlighted with earlier findings [60,61].

Our study has revealed that the environmental factors such as: solar radiation, Precipitation of Warmest Quarter and elevation have significantly mediated the distributions of the potential suitable habitats of the two study species (Table 2) and. For example, precipitation seasonality and precipitation of driest quarter are the drivers of the distribution of the suitable habitats of *Pouteria adolfi-friederici* while mean monthly temperature and temperature of coldest quarter are predicted to affect the habitat suitability ranges of *Prunus africana* in Ethiopia (Table 2). Understandably, such trends of fluctuations in distributions of suitable habitats may arise from the fact that the plant species have their own specific optimum demands for temperature, precipitation and altitudinal range. In this nexus, [52] from Nepal reported that the temporal variations in temperatures and precipitations are the key factors for fluctuations of the adaptive

ranges of habitats suitability for plant species. On the other hand, in the tropics, the magnitude of the solar radiation remains a constant input under both current and the future climate scenarios and as a result may not be accountable for the variations of the distributions of the potential suitable habitats of the different plant species (Table 4 and 5). Of course, the significance of the impacts of these environmental factors is related to the elevational gradients. As a result, different plant species may move out of their fundamental niches and occupy the realized ecological zones; yet, if failed to adapt may go extinct under the future climate change scenarios [62,63]. Unequivocally, several previous findings have related that change in climatic conditions alter the distributions of biological species [64–66].

Among the biological characteristics that limit the distributions of the plant species could be their dispersal mechanisms besides the impacts of climatic change [2]. Thus, despite the southern parts of the southwest regions and west central areas will be highly suitable habitat potentials for *Pouteria adolfi-friederici* and *Prunus africana*, the species may not fully occupy the predicted suitable habitats due to the recalcitrant nature of their seeds, which are sensitive to fluctuation of environmental factors and liable to pest attack and disease damages [67,68]. Moreover, their seeds may not reach the suitable areas because of limitations of appropriate dispersal agents of the species.

Patterns of distribution of suitable habitats in relation to major vegetation types

The prediction models indicated that, under all the climate scenarios, moist afro-montane, dry afro-montane and *Combretum-Terminalia* woodland vegetation types were found to be highly suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* during the periods of 2050 and 2070 (Fig 8 and 9). Moreover, from other group of vegetation types, the riverine vegetation was

identified to be a high suitable habitat of *Prunus africana*, which is most likely favoured by microrefugia habitat moderated by local climate condition (mainly moisture) associated with riverine. The highly suitable areas identified for *Pouteria adolfi-friederici* within *Combretum-Terminalia* woodland vegetation are contributed due to the presence of confined suitable habitats of the species within *Combretum-Terminalia* woodland and in the ecotones that moist afro-montane and dry afro-montane vegetation types share with the *Combretum-Terminalia* woodland vegetation type (Fig 4 and 8).

The highly suitable areas of *Prunus africana* in *Combretum-Terminalia* was identified for RCP 4.5 by 2050 embedded in ecotones in the transition among moist afro-montane, *Combretum-Terminalia* and dry afro-montane vegetation types (Fig 5 and 9). However, these habitats seem to be unfavorable for the species under RCP 8.5, may be due to the impact of high temperature that is assumed to increase under this trajectory than the current and RCP 4.5 scenarios.

The spatial distributions of potential suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* showed significant shifts along elevational gradients under the current and future climate scenarios (Table 3). Similarly, topographic position was found to be important factor in driving the distributions of the suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* tree species, but such impact was not found for elevation and solar radiation (Table 4 and 5).

In terms of the relative proportions of the areas predicted to be suitable habitats for both tree species, the trend show that the areas are decreasing under future climate scenarios when compared with the current status (Fig 6 and 7). In this connection, our results corroborate the earlier findings that pointed out that climate change is highly responsible for the area contraction of suitable habitats of plant species [52,69–72]. In general, it is of quite importance to undertake the prediction models of the effects of climate change on the distributions of suitable habitats of

floras not only just in terms of area shift but also by ecosystems and biomes. Moreover, the present study is limited only to exploration of the impacts of the bioclimatic variables including solar radiation, elevation and topographic position indices and it may also be interesting to examine the effects of other factors such as soil types on the distribution of floras during this changing climate conditions under the current and future scenarios.

Conclusions

The impacts of climate change and topographic factors are critical to determine the distributions of the suitable habitats for plant species. In this regard, our study denoted that the environmental factors such as, elevation, solar radiation, topographic positions, temperature and precipitation have significantly contributed in the prediction models of the distributions of the potential suitable habitats of *Pouteria adolfi-friederici* and *Prunus africana* tree species under the future climate scenarios of 2050 and 2070 periods. During these periods, the highly suitable habitats of both tree species showed spatial and elevational shifts. For example, there is a shift of highly suitable habitats of *Pouteria adolfi-friederici* from the north and central parts of the southwest MAF to its southern areas according to the RCPs scenarios. Similarly, the highly suitable habitats of *Prunus africana* was predicted to shift from the western areas of Ethiopia to the west central regions. By sum, from our study, we conclude that the strategies wish to design national biodiversity conservation should take into account dynamics of the suitable niches of different species under changing climate scenarios.

Acknowledgements

We thank the National Herbarium of Addis Ababa University for permitting us to collect species presence data from the authenticated specimens in it. Finally, we extend our heartfelt thanks to

Prof. Sebsebe Demissew, Prof. IB Friis, and Van Breugel, Paulo for supplying us the shape file of the Potential Vegetation Types Atlas of Ethiopia to use for designing the study area of our study.

Authors contributions

The authors have equal contributions on participating in designing the study, collecting and analyzing data, interpreting and drawing conclusions of the findings of the study.

References

1. Bambach N, Meza FJ, Gilabert H, Miranda M. Impacts of climate change on the distribution of species and communities in the Chilean Mediterranean ecosystem. *Reg Environ Change*. 2013;13:1245-1257.
2. Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F. Impacts of climate change on the future of biodiversity. *Ecol Lett*. 2012;15:365-377.
3. Peterson AT, Soberón J. Species distribution modeling and ecological niche modeling: getting the concepts right. *Perspect Ecol Conserv*. 2012; 10:102-107.
4. Boudiaf B, Dabanli I, Boutaghane H, Şen Z. Temperature and precipitation risk assessment under climate change effect in northeast Algeria. *Earth Syst. Environ*. 2020; 1-14. <https://doi.org/10.1007/s41748-019-00136-7>
5. Arnell N, Reynard N. The effects of climate change due to global warming on river flows in Great Britain. *J Hydrol (Amst)*. 1996;183:397-424.
6. Arnell NW. Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: future streamflows in Britain. *J Hydrol (Amst)*. 2003; 270:195-213.

991 7. Houghton J. Global warming. Rep Prog Phys. 2005; 68:1343. Available:
992 <http://iopscience.iop.org/journal/0034-4885>

993 8. MacKinnon K, Sobrevila C, Hickey V. Biodiversity, climate change, and adaptation: nature-
994 based solutions from the World Bank portfolio. The World Bank, 2008. Available:
995 [http://documents.worldbank.org/curated/en/149141468320661795/Biodiversity-climate-](http://documents.worldbank.org/curated/en/149141468320661795/Biodiversity-climate-change-and-adaptation-nature-based-solutions-from-the-World-Bank-portfolio)
996 [change-and-adaptation-nature-based-solutions-from-the-World-Bank-portfolio](http://documents.worldbank.org/curated/en/149141468320661795/Biodiversity-climate-change-and-adaptation-nature-based-solutions-from-the-World-Bank-portfolio).

997 9. Houghton J. Global warming: the complete briefing. Cambridge university press; 2009.

998 10. McCarthy MP, Best MJ, Betts RA. Climate change in cities due to global warming and urban
999 effects. Geophys Res Lett. 2010; 37. Doi: [10.1029/2010GL042845](https://doi.org/10.1029/2010GL042845).

1000 11. Lineman M, Do Y, Kim JY, Joo GJ. Talking about climate change and global warming. *PLoS*
1001 *one*. 2015; 10:e0138996. Available: <https://doi.org/10.1371/journal.pone.0138996>

1002 12. Bein T, Karagiannidis C, Quintel M. Climate change, global warming, and intensive care.
1003 Intensive Care Med. 2019; 46:485–487. Available: [https://doi.org/10.1007/s00134-019-](https://doi.org/10.1007/s00134-019-05888-4)
1004 [05888-4](https://doi.org/10.1007/s00134-019-05888-4)

1005 13. Hansen J, Sato M, Ruedy R, Lo K, Lea DW, Medina-Elizade M. Global temperature change.
1006 2006; 103:14288-14293. Available: [www.pnas.org/cgi/doi10.1073](https://www.pnas.org/cgi/doi/10.1073/pnas.0606291103) pnas.0606291103.

1007 14. New M, Liverman D, Schroder H, Anderson K. Four degrees and beyond: the potential for a
1008 global temperature increase of four degrees and its implications. The Royal Society
1009 Publishing; 2011.

1010 15. Huntingford C, Jones PD, Livina VN, Lenton TM, Cox PM. No increase in global
1011 temperature variability despite changing regional patterns. Nature. 2013; 500:327-330.

1012 16. Rastogi M, Singh S, Pathak H. Emission of carbon dioxide from soil. Curr Sci. 2002; 82:510-
1013 517. Available: <https://www.jstor.org/stable/24105957>

- 1014 17. Solomon S, Plattner GK, Knutti R, Friedlingstein P. Irreversible climate change due to
1015 carbon dioxide emissions. PNAS.2009; 106:1704-1709. Available:
1016 <https://doi.org/10.1073/pnas.081272110>
- 1017 18. Kajaste R., Hurme M. Cement industry greenhouse gas emissions–management options and
1018 abatement cost. J Clean Prod. 2016; 112:4041-4052.
- 1019 19. Pachauri RK, Reisinger A. IPCC fourth assessment report. *IPCC, Geneva*; 2007.
- 1020 20. Woodward A, Smith KR, Campbell-Lendrum D, Chadee DD, Honda Y, Liu Q, et al. Climate
1021 change and health: on the latest IPCC report. The Lancet. 2014; 383:1185-1189.
- 1022 21. Hannah L, Midgley G, Lovejoy T, Bond W, Bush M, Lovett J, et al. Conservation of
1023 biodiversity in a changing climate. Conserv Biol. 2002; 16:264-268.
- 1024 22. Kannan R, James. Effects of climate change on global biodiversity: a review of key
1025 literature. Trop Ecol. 2009; 50:31.
- 1026 23. Scarano FR. Biodiversity sector: risks of temperature increase to biodiversity and
1027 ecosystems, Climate change risks in Brazil. Springer. 2019; 131-141. DoiI: [10.1007/978-](https://doi.org/10.1007/978-3-319-92881-4_5)
1028 [3-319-92881-4_5](https://doi.org/10.1007/978-3-319-92881-4_5)
- 1029 24. Lovejoy TE. Climate change and biodiversity. ISBN 81-7993–084-X; 2006. Available:
1030 <https://citeseerx.ist.psu.edu>
- 1031 25. García FC, Bestion E, Warfield R, Yvon-Durocher G. Changes in temperature alter the
1032 relationship between biodiversity and ecosystem functioning. PNAS. 2018; 115:10989-
1033 10994.
- 1034 26. Parain EC, Rohr RP, Gray SM, Bersier L.F. Increased temperature disrupts the biodiversity–
1035 ecosystem functioning relationship. Am Nat. 2019; 193:227-239.

- 1036 27. Perrings C. Biodiversity, ecosystem services, and climate change. The Economic
1037 Problem/Environment department papers. 2010; 120:1-39. Available:
1038 <https://openknowledge.worldbank.org>.
- 1039 28. Rinawati F, Stein K, Lindner A. Climate change impacts on biodiversity—the setting of a
1040 lingering global crisis. Divers. 2013; 5:114-123.
- 1041 29. Louthan AM, Doak DF, Angert AL. Where and when do species interactions set range
1042 limits? Trends Ecol Evol. 2015; 30:780-792.
- 1043 30. Hedberg I, Edwards S. Flora of Ethiopia: Pittosporaceae to Araliaceae: the National
1044 Herbarium. Uppsala: Addis Ababa, Ethiopia, and Department of Systematic Botany;
1045 1989; 3.
- 1046 31. Hedberg I, Edwards S, Nemomissa S. Flora of Ethiopia and Eritrea: Apiaceae to
1047 Dipsacaceae. Addis Ababa, Ethiopia and Uppsala, Sweden: The National Herbarium,
1048 Addis Ababa University; 2003; 4: 1.
- 1049 32. Friis I, Demissew S, van Breugel P. Atlas of the potential vegetation of Ethiopia. Det
1050 Kongelige Danske Videnskabernes Selskab; 2010.
- 1051 33. Negash L. Indigenous trees of Ethiopia. *Biology, uses and propagation techniques*. SLU
1052 *Reprocentralen*, Umeå, Sweden; 1995.
- 1053 34. Bekele T, Berhan G, Taye E, Ersado M, Yeshitela K. Regeneration status of moist Montane
1054 forest of Ethiopia: Consideration for Conservation part. Walia. 2001:45-62. Available:
1055 <https://www.researchgate.net/publication/313988325>
- 1056 35. Lemenih M, Teketay D. Restoration of native forest flora in the degraded highlands of
1057 Ethiopia: constraints and opportunities. SINET. 2004; 27:75-90.

36. Cunningham A, Anoncho V, Sunderland T. Power, policy and the *Prunus africana* bark trade, 1972–2015. J Ethnopharmacol. 2016; 178:323-333.
37. Stewart KM. The African cherry (*Prunus africana*): can lessons be learned from an over-exploited medicinal tree? J Ethnopharmacol. 2003 Nov;89(1):3-13. doi: 10.1016/j.jep.2003.08.002. PMID: 14522426.
38. World Conservation Monitoring Centre. 1998. *Prunus africana*. The IUCN Red List of Threatened. e.T33631A9799059; 1998. Available: <https://dx.doi.org/10.2305/IUCN.UK.Species.1998.T33631A9799059.en>.
39. Kadu CA, Parich A, Schueler S, Konrad H, Muluvi GM, Eyog-Matig O, et al. Bioactive constituents in *Prunus africana*: geographical variation throughout Africa and associations with environmental and genetic parameters. Phytochemistry. 2012; 83:70-78.
40. Lompo D, Vinceti B, Konrad H, Gaisberger H, Geburek T. Phylogeography of African locust bean (*Parkia biglobosa*) reveals genetic divergence and spatially structured populations in West and Central Africa. J Hered. 2018; 109:811-824.
41. McCann JC. The plow and the forest: narratives of deforestation in Ethiopia, 1840-1992. Environ Hist Durh N C. 1997; 2:138-159.
42. Getahun K, Rompaey AV, Turnhout PV, Joesen J. Factors controlling patterns of deforestation in moist evergreen Afromontane forests of Southwest Ethiopia. For Ecol Manage. 2013; 304: 171-181.
43. Guillozet K, Bliss JC, Kelecha TS. Degradation in an Afromontane forest in highland Ethiopia, 1969–2010. Small-Scale For. 2015; 14:121-137.

- 1080 44. EFCCC. Ethiopia's Forest Reference Level Submission to the UNFCCC. 2017; 1-77.
1081 Available: <http://redd.unfccc.int> › files › ethiopia_frel_3.2_fi...
- 1082 45. Diffenbaugh NS, Giorgi F. Climate change hotspots in the CMIP5 global climate model
1083 ensemble. *Clim Change*. 2012; 114:813-822.
- 1084 46. He C, Zhou T. Responses of the western North Pacific subtropical high to global warming
1085 under RCP4. 5 and RCP8. 5 scenarios projected by 33 CMIP5 models: The dominance of
1086 tropical Indian Ocean–tropical western Pacific SST gradient. *J Clim*. 2015; 28:365-380.
- 1087 47. Brown SC, Wigley TM, Otto-Bliesner BL, Rahbek C, Fordham DA. Persistent Quaternary
1088 climate refugia are hospices for biodiversity in the Anthropocene. *Nat Clim Chang*. 2020;
1089 10:244-248.
- 1090 48. Reisinger A, Meinshausen M, Manning M. Future changes in global warming potentials
1091 under representative concentration pathways. 2011; Doi: 10.1088/1748-9326/6/2/024020.
- 1092 49. Brown JL. SDMtoolbox: a python-based GIS toolkit for landscape genetic, biogeographic
1093 and species distribution model analyses. *Methods in Ecology and Evolution*. *Methods Ecol*
1094 *Evol*. 2014; 5: 694–700. Doi: 10.1111/2041-210X.12200.
- 1095 50. Barbosa FG, Pillar VD, Palmer AR, Melo AS. Predicting the current distribution and
1096 potential spread of the exotic grass *Eragrostis plana* Nees in South America and
1097 identifying a bioclimatic niche shift during invasion. *Austral Ecol*. 2013; 38:260-267.
- 1098 51. Vega GC, Pertierra LR, Olalla-Tárraga MÁ. MERRAclim, a high-resolution global dataset of
1099 remotely sensed bioclimatic variables for ecological modelling. *Sci Data*. 2017; 4:1-12.
- 1100 52. Chhetri PK, Gaddis KD, Cairns DM. Predicting the suitable habitat of treeline species in the
1101 Nepalese Himalayas under climate change. *Mt Res Dev*. 2018; 38:153-163.

- 1102 53. Ma B, Sun J. Predicting the distribution of *Stipa purpurea* across the Tibetan Plateau via the
1103 MaxEnt model. *BMC Ecol.* 2018; 18: 1-12.
- 1104 54. Phillips SJ, Anderson RP, Schapire RE. Maximum entropy modeling of species geographic
1105 distributions. *Ecol Modell.* 2006; 190:231-259.
- 1106 55. Fan J, Upadhye S, Worster A. Understanding receiver operating characteristic (ROC) curves.
1107 *CJEM.* 2006; **8**:19-20.
- 1108 56. Fourcade Y, Engler JO, Rödder D, Secondi J. Mapping species distributions with MaxEnt
1109 using a geographically biased sample of presence data: a performance assessment of
1110 methods for correcting sampling bias. *PloS one* 9:e97122. 2014; 9:
1111 <https://doi.org/10.1371/journal.pone.0097122>
- 1112 57. Araújo MB, Pearson RG, Thuiller W, Erhard M. Validation of species–climate impact
1113 models under climate change. *Glob Chang Biol.* 2005; 11:1504-1513.
- 1114 58. R Foundation for Statistical Computing, Vienna, Austria; 2021. Available: URL
1115 <http://www.R-project.org/>.
- 1116 59. Stalin N, Swamy P. Prediction of suitable habitats for *Syzygium caryophyllatum*, an
1117 endangered medicinal tree by using species distribution modelling for conservation
1118 planning. *Eur J Exp Biol.* 2015; 5:12-19.
- 1119 60. Buckley LB, Urban MC, Angilletta MJ, Crozier LG, Rissler LJ, Sears MW. Can mechanism
1120 inform species' distribution models? *Ecol Lett.* 2010; 13:1041-1054.
- 1121 61. Shirk AJ, Cushman SA, Waring KM, Wehenkel CA, Leal-Sáenz A, Toney C, et al.
1122 Southwestern white pine (*Pinus strobiformis*) species distribution models project a large
1123 range shift and contraction due to regional climatic changes. *For Ecol Manage.* 2018;
1124 411:176-186.

- 1125 62. Provan J, Maggs CA. Unique genetic variation at a species' rear edge is under threat from
1126 global climate change. *Proc R Soc Lond B Biol Sci.* 2012; 279:39-47.
- 1127 63. Zhang K, Zhang Y, Zhou C, Meng J, Sun J, Zhou T, et al. Impact of climate factors on future
1128 distributions of *Paeonia ostii* across China estimated by MaxEnt. *Ecol Inform.* 2019;
1129 50:62-67.
- 1130 64. Zhu K, Woodall CW, Clark JS. Failure to migrate: lack of tree range expansion in response
1131 to climate change. *Glob Chang Biol.* 2012; 18:1042-1052
- 1132 65. Gül S, Kumlutaş Y, Ilgaz C. Potential distribution under different climatic scenarios of
1133 climate change of the vulnerable Caucasian salamander (*Mertensiella caucasica*): A case
1134 study of the Caucasus Hotspot. *Biol Futur.* 2018; 73:175-184.
- 1135 66. Wei B, Wang R, Hou K, Wang X, Wu W. Predicting the current and future cultivation
1136 regions of *Carthamus tinctorius* L. using MaxEnt model under climate change in China.
1137 *Glob Ecol Conserv.* 2018; 16:e00477.
- 1138 67. Albrecht J. Tree Seed Handbook of Kenya. Kenyan Forestry Research Institute and GTZ
1139 Forestry Seed Centre Muguga, Nairobi; 1993.
- 1140 68. Lemmens RH. *Pouteria adolfi-friedericii* (Engl.) A.Meeuse. In: Louppe, D., Oteng-Amoako,
1141 A.A. & Brink, M. (Editors). PROTA (Plant Resources of Tropical Africa / Ressources
1142 végétales de l'Afrique tropicale), Wageningen, Netherlands; 2007.
- 1143 69. Hampe A, Petit RJ. Conserving biodiversity under climate change: the rear edge matters.
1144 *Ecol Lett.* 2005; 8:461-467.
- 1145 70. Bridle JR, Vines TH. Limits to evolution at range margins: when and why does adaptation
1146 fail? *Trends Ecol Evol.* 2007; 22:140-147.

1147 71. Cobos ME, Peterson AT, Barve N, Osorio-Olvera L. kuenm: an R package for detailed
1148 development of ecological niche models using Maxent. PeerJ. 2019; 7:e6281.

1149 72. Gao T, Xu Q, Liu Y, Zhao J, Shi J. Predicting the Potential Geographic Distribution of *Sirex nitobei*
1150 in China under Climate Change Using Maximum Entropy Model. Forests. 2012; 12:151.

1151

1152

1153

1154

1155

1156

1157

1158

1159

1160

1161

1162

1163

1164

1165

1166

1167

1168

1169

Figures Cations

Fig 4. The current occurrences of *Pouteria adolfi-friederici* and *Prunus africana* tree species across five major vegetation types of Ethiopia.

Fig 2. Response curves of four top contributing variables to distribution of *Pouteria adolfi-friederici*: solar radiation, Precipitation of Warmest Quarter, Precipitation of Driest Quarter and Precipitation Seasonality.

Fig 3. Response curves of four top contributing variables to distribution of *Prunus africana*: solar radiation, mean temperature of coldest quarter, precipitation of warmest quarter and elevation.

Fig 4. Spatial prediction models of the distributions of habitat suitability for *Pouteria adolfi-friederici* under current and future climate scenarios.

Fig 5. Spatial prediction models of the distributions of habitat suitability for *Prunus africana* under current and future climate scenarios.

Fig 6. Relative area proportion (%) of suitable habitat categories of *Pouteria adolfi-friederici* under current and future climate scenarios.

Fig 7. Relative area proportion (%) of suitable habitat categories of *Prunus africana* under current and future climate scenarios.

Fig 8. Relative area proportion (%) of suitable habitats of *Pouteria adolfi-friederici* by major vegetation types under current and future climate scenarios.

Fig 9. Relative area proportion (%) of suitable habitats of *Prunus africana* by major vegetation types under current and future climate scenarios.

1194 **Supporting Information**

1195 S1 Table. Correlation matrix among 19 current bioclimatic variables, elevation, solar radiation
1196 and topographic position indices (done using SDM_v2.4_AcrMap 10.5).

1197

1198

1199

1200

1201

Map of Vegetation of Ethiopian

bioRxiv preprint doi: <https://doi.org/10.1101/2021.08.12.456155>; this version posted August 12, 2021. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY 4.0 International license.

Legend

- *P. adolfi frederici*
- *P. africana*
- Acacia_Commiphora*
- Others
- Combretum_Terminalia*
- Dry Afromontane
- Moist Afromontane

Figure

Figure

Figure

P. adolfi-friederici

Legend

- Highly suitable
- Suitable
- Moderately suitable
- Less suitable
- Acacia_Commiphora*
- Combretum_Terminalia*
- Dry Afromontane
- Moist Afromontane
- Others

0 125 250 500 Kilometers

bioRxiv preprint doi: <https://doi.org/10.1101/2021.08.12.456155>; this version posted August 12, 2021. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY 4.0 International license.

Figure

P. africana

Legend

- Highly suitable
- Suitable
- Moderately suitable
- Less suitable
- Acacia_Commiphora*
- Combretum_Terminalia*
- Dry Afromontane
- Moist Afromontane
- Others

Current

0 125 250 500 Kilometers

bioRxiv preprint doi: <https://doi.org/10.1101/2021.08.12.456155>; this version posted August 12, 2021. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY 4.0 International license.

4.5RCP2050

4.5RCP2070

8.5RCP2050

8.5RCP2070

P. adolfi-friederici

Figure

P. africana

Figure

Figure

Legend

- Highly suitable
- Suitable
- Moderately suitable
- Less suitable

Figure