Modeling the impacts of climate change and cochineal (*Dactylopius coccus* Costa) invasion on the future distribution of cactus pear (*Opuntia ficus-indica* (L.) Mill.) in Northern Ethiopia

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ABSTRACT

This study investigated that the effects of cochineal invasion and climate change on cactus pear distribution. Rainfall and temperature were projected to near, mid, and end-century with emission scenarios (RCP4.5 and 8.5) using R-programing language. Average temperature will be increased by 1.7, 2.3, and 2.6°C in RCP 4.5 and 2, 2.8, and 4°C in RCP 8.5 at 2010-2039, 2040-2069, and 2070-2099, respectively, and there will be temporal and spatial rainfall variation. The cactus pear distribution will be reduced by 13, 0.51, and 27% during mid-century of RCP 4.5 and RCP8.5, and RCP8.5 of end-century, consistently. But, it will be increased by 0.8% at the end-century of RCP4.5. The impact of climate change in future cactus pear distribution is insignificant. In addition, the probability of cochineal invasion will be increased by about 72, 74, 62, and 94% by mid and end-century of RCP4.5 and 8.5, respectively. This has a significant impact on future cactus pear distribution. The combined effect of climate change and cochineal invasion will affect 72, 78, 63, and 85% of cactus pear distribution by mid and end-century of RCP4.5 and 8.5, respectively. It has a significant impact on future cactus pear distribution. Therefore, the study recommends well-designed management strategies to ensure cactus pear survival.

Keywords: Maxent, bioclimatic variables, suitability, global warming, drought.

INTRODUCTION

Ethiopia is exposing to climate change because of low adaptive capacity. An average decadal temperature of Tigray (northern Ethiopia) is increasing at the rate of 0.54ºC which is more than double, compared to the countrywide average of 0.25ºC per decade (Gebrehiwot and Veen, 2013). This increasing of temperature results a drought (Gebre *et al*., 2013). To cope up those effects, communities in such an environment should depend on climate change resilience and adaptation mechanism (Belay *et al*., 2006).

The ability to select adaptive plant species that can co-exist and produce yields in drought season is an important mechanism for resilience and adaptation. In the study area, cactus pear is used to build adaptive capacity of communities during drought and rain period (Belay *et al*., 2006). Cactus pear is drought tolerant species (Belay, 2015). Its fruit helps as the source of food before harvesting of cereal crops. Cactus pear is the most commonly cultivated species throughout the world (FAO, 2013). This species is also commonly found in Ethiopia, especially in the northern part called Tigray (Belay, 2015).

Cactus pear is used as food, forage, the source of income, soil and water conservation, medicinal, cosmetics, and drought insurance crop. However, cactus pear is a neglected and less researched plant in Ethiopia (Belay, 2015). The species grows in marginal lands, which do not use for other crops (Haile *et al*., 2000). Cactus pear grows under stress conditions, including poor management practices. Together with improper cultivation and management, it is severely affecting through cochineal invasion. Cochineal was introduced to the country in 2004 as a beneficial insect in three selected sites namely Endayesus, Tsehafti and Embachara for the production of dye (Belay *et al*., 2006). It was about 30 ha in 2007 (Belay, 2010); but in 2014 it has invaded about 16,255.25 ha of cactus pear (Belay, 2015). Cochineal is using for production of dye (Serrano *et al*., 2013). The dye extracted from cochineal (*Dactylopius coccus*) is rich in carminic acid (Reyes Agüero *et al*., 2005) and used for coloring of food and cosmetics, textiles (Serrano *et al*., 2013) and drugs (Canamares *et al*., 2006). Cochineal of Tigray region has higher carminic acid than other places due to the presence of the highest phosphorus content in soil (Tesfay and Bustamante, 2010).

Cochineal is a soft body, flat, oval-shaped scale insect (Esalat Nejad and Esalat Nejad, 2013). Cochineal life cycle varies according to their sex. The female life cycle has two nymph and one adult stage, whereas the male passes through four nymph stages. The first two instars being comparable to that of the female but the third and fourth are characterized by a pre-pupa and pupa stage (Bosso *et al*., 2013; Flores-Hernández *et al*., 2006). Additionally, female cochineal metamorphosis is incomplete whereas male is complete metamorphosis (Flores-Hernández *et al*., 2006). The life cycle of cochineal varies based on climatic variables such as temperature and it ranges from 90 to 128 (Inglese *et al*., 2017). Cochineal breeding is affected by temperature rain, wind, light (Flores, 1995). Female cochineal mostly lay up to 420 eggs (Inglese *et al*., 2017).

Hence, cochineal is affecting by temperature and rainfall variations (Rao *et al.*, 2013). Additionally, climate change and variability facilitate pest invasion rate through increasing temperature and decreasing rainfall (Badii and Flores, 2001). Climate change may also affect the cactus pear potential through directly and indirectly such as pest and disease (Cortes *et al.*, 2013). Trend and effect of climate change are predicting using different General Circulation Models (GCM), Representative Concentration Pathways (RCPs) and time slices. RCPs are used as inputs for climate modeling and are affected by concentrations of a variety of greenhouse gases, land use change, environmental pollution, technology development, population, energy use (Moss *et al.*, 2010).

Nowadays, cactus pear is becoming a threatened species, which requires effective management activities. Thus, effective species conservation further requires accurate knowledge of species geographical distribution modeling (Groff, 2011). Species Distribution Models (SDMs) are important to predict the geographic distributions of different species to determine today's, as well as future conditions. Based on such analyses, it will be possible to indicate the potential distribution of the species where conditions are favorable or not for the studied species (Abrha *et al.*, 2018). This study, therefore, had tried to model the individual and coupled effect of cochineal invasion and climate change on future cactus pear distribution. The result aims that an investigation of well-matched adaptation solutions by various societal categories, policy makers, governmental and non-governmental organizations.

MATERIALS AND METHODS

Study areas

Tigray region is found between the latitude of 12°15' and 14°57' north, and longitude of 36°27' and 39°59' east, in northern Ethiopia. It has an altitude from about 500 to almost 4000 m.a.s.l. (Kassa *et al.*, 2014). It covers about 53,000 km^2. As the data taken from Ethiopian national meteorological agency showed, annual average temperature and rainfall of Tigray ranges from 12-37°C and 500-1000 mm respectively. Cambisols, fluvisols, rendzinas, leptosols, fluvisols, nitosols, arenosols, vertisols, xerosols, regosols, luvisols calcisols, and andosols are the major soils of the region (Nyssen *et al.*, 2008).

More than 85% of the population is dependent on agriculture (Brutsch, 1997). It consists of crop and animal production, both in isolation and mixed farm (Kassa *et al.*, 2014). Farmers are using the traditional farming system such as crop rotation, animal manure, fallowing, and wood ash to improve soil fertility and productivity (Edwards *et al.*, 2010). Tigray has about 360,000 ha of cactus pear (Brutsch, 1997). Its eastern, southeastern, and southern zones have high cactus pear potential, and based on their cactus pear resources, one district from each zone was purposively selected. The districts were Ganta Afeshum, Hintalo Wejerat, and Raya Azebo from an eastern, southeastern, and southern zone, respectively (Figure 1).

Ganta Afeshum is found in the latitude of 14° 20′ north and longitude of 39° 15′ east. It covers about 1,636.36 km^2. Its average annual rainfall is 595 mm. Its average annual maximum and minimum temperatures of the district are 24.6 and 6.1°C, respectively. The major cultivated crops in the district are barley, wheat, sorghum, maize, finger millet, and pulses (Tesfaye, 2010).

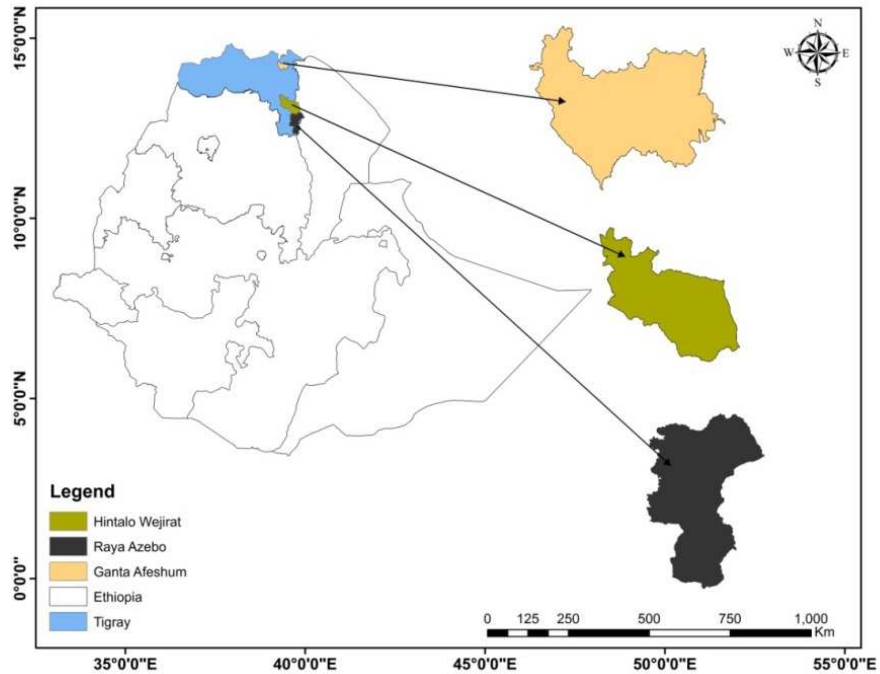

Figure 1. Map of the study areas.

Raya Azebo is located in 12° 17' and 12° 15' North Latitude and 39° 22' to 39° 25 east longitude. The average annual temperature of the district is 21.5°C. Its mean annual rainfall is 779 mm with a bimodal type pattern in summer and spring. However, most of the year potential evapotranspiration is high and exceeds rainfall (Bewket and Radeny, 2015). The major crops grown in the Woreda are sorghum, teff, and maize. The main livestock is cattle, sheep, goats, and camel. Crop residue and chopped cactus pear are used for animal feed.

Hintalo-Wejerat is located between13° 15' north and longitude 39° 31' east. Its average annual rainfall and temperature are 598 mm and 19.8°C, respectively. The total land size of the district is about 98,100 ha and from this 36,107 ha is cultivated the land. The major cultivated cereal crops in the district are barley, sorghum, wheat, teff, pulses and cash crops (cabbages, carrot, potatoes, onion, and tomatoes) (Tesfaye, 2010). Livestock is also a source of money for the community. The major feed source for livestock is crop residues, communal grazing, chopped cladodes of cactus pear, and to some extent grass hay harvested from farmland borders, exclosures and backyards (Tesfaye, 2010). Therefore, cactus pear is commonly used for food, feed, income sources and other ecological roles in the three districts.

Data sources

Local climate data

Climatic variables used in this study were daily rainfall, daily average minimum and maximum temperatures of the past 30 years (1980-2009). These were found from Ethiopian National Meteorological Agency and satellite data (AgMERRA). These were used to project and to know the future trend of rainfall and temperature in the study area.

GenStat 14th edition software was used to arrange the NMA climate data in order to make it compatible with R-package software. It was incomplete and was filled with the satellite data. The filled baseline climate data was projected to three-time slices (2010-2039, 2040-2069, 2070-2099) with scenario of two emissions (RCP 4.5 and 8.5) under one GCM in R-package software. The RCP's were selected, as they constitute medium and high emission scenario, which will be helpful for best recommendations. The prediction was used to prove the climate change and variability of the study area.

The GCMs selected for the study were GCM-1 (ACCESS1-0), GCM-5 (CCSM4) and GCM-15 (MIROC5). These GCMs have relatively higher consistency and they are widely used in sub-Saharan Africa (Rosenzweig *et al*., 2013; Hudson and Ruane, 2013).

Six years locally observed data of temperature and rainfall (2010-2015) were correlated with same six years (matched) projected data using those three GCMs, in order to choose the GCM which expressed the highest correlation with the observed local data. Normality test was performed prior to correlation. The distribution of temperature data was normal; however for the rainfall data was not normally distributed (for current and all GCMs). Hence, Pearson and Spearman correlation were used for temperature and rainfall data, respectively (Tables 1 and 2).

Table 1. Pearson correlation coefficient for average monthly temperature

	RCP4.5			RCP8.5		
	GCM 1	**GCM 5**	**GCM 15**	**GCM 1**	**GCM 5**	**GCM 15**
Current	0.92**	0.95**	0.93**	0.88**	0.93**	0.89**
Significance	0.00	0.00	0.00	0.00	0.00	0.00

**Correlation is significant at 0.01 level.

Table 2. Spearman correlation coefficient for average monthly rainfall

	RCP4.5			RCP8.5		
	GCM1	**GCM5**	GCM15	GCM1	**GCM5**	GCM15
Current	0.340	**0.640***	0.400	0.330	**0.620***	0.25
Significance	0.226	0.024	0.199	0.297	0.031	0.43

*Correlation is significant at 0.05 level

The projected temperatures of the three GCMs in both RCPs were correlated significantly ($p < 0.01$) with observed local data. However, only one GCM (GCM5) was significantly correlated ($p < 0.05$) with observed local rainfall data in both RCPs. Hence, the two GCMs (GCM 1 and GCM 15) were dropped, as they were not significantly correlated with observed rainfall data. As a result, the research was conducted using only GCM-5 namely Climate Community System Model Version 4 (CCSM4).

Cactus pear and cochineal data collection

A total of 257 and 182 cactus pear and cochineal presence points were collected, respectively (Figure 2). These presence location points were sufficed to run the model, as species distribution models with locations more than 30 occurrence points' results in a more precise and accurate prediction (Baldwin, 2009).

Figure 2. Cochineal infestation on cactus pear.

Bioclimatic data

Bioclimatic data are the major requirements for the analysis of current and future distribution changes for the target species. Hence, 19 Bioclimatic data and altitude with 30 arc-second resolution (1 km^2) were obtained from the *World Climate* (http://www.worldclim.org) and downloaded from GCM-5 and RCP 4.5 and 8.5 (Table 3). Then it was clipped down in Arc GIS to Tigray map shape file.

Soil data

Soils are more effective for natural resources evaluation (Rabia *et al*., 2013). For more than 30 years the FAO/UNESCO Soil layer of the World was the only soil layer available at a scale of

1:5 Million. However, later it was known that the soil information in the map was deficient in many areas and improved by Harmonized World Soil Database (HWSD) which announced new global soil information (Nachtergaele *et al*., 2012).

Table 3. Bioclimatic variables.

Code	Bioclimatic variable	Factor
bio01	annual mean temperature	10
bio02	mean diurnal range [mean of monthly (max temp - min temp)]	100
bio03	isothermality [(bio02/bio07)*100]	100
Bio04	temperature seasonality (standard deviation *100)	10
bio05	max temperature of warmest month	10
bio06	min temperature of coldest month	10
bio07	temperature annual range (bio05-bio06)	10
bio08	mean temperature of wettest quarter	10
bio09	mean temperature of driest quarter	10
bio10	mean temperature of warmest quarter	10
bio11	mean temperature of coldest quarter	1
bio12	annual precipitation	1
bio13	precipitation of wettest month	1
bio14	precipitation of driest month	100
bio15	precipitation seasonality (coefficient of variation)	1
bio16	precipitation of wettest quarter	1
bio17	precipitation of driest quarter	1
bio18	precipitation of warmest quarter	1
bio19	precipitation of Coldest Quarter	1
20	Altitude	1

Source: Dupin *et al.* (2011); Escobar *et al*. (2016).

Harmonized World Soil Database (HWSD), which is improved to cover for about 60% of the land area as compared to the FAO/UNESCO Soil layer of the World. It is produced with a 30 arc-second resolution (Nachtergaele *et al*., 2012). This was also improved by the International Soil Resources Information Center (ISRIC), an institution that is the source of the soil data for the study (Table 4). Generally, all environmental variables (ISRIC soil data, Altitude, and 19 Bioclimatic variables) were used with the same resolution, which was 30 arc-second.

Cactus pear presence

Cactus pear presence is an explanatory variable for the cochineal invasion because when the software runs without cactus pear presence, the distribution of cochineal did not match with actual cochineal presence. However, when running with cactus pear presence, the actual cochineal presence (infestation) and its predicted distribution rely upon similar place. Hence, it is among the variables that determine the invasion of cochineal. Cochineal is also specific pest, which only stays alive on its host named cactus pear. Therefore, cactus pear presence map was then used as input variable together with the above noted environmental variables to project the future cochineal invasion. It was generated from own using maximum entropy model (Maxent 3.3.3k) (Phillips *et al*., 2006). Accordingly, 19 bioclimatic data, altitude, cactus pear presence, and soil data were used as input variables to develop the two species (cochineal and cactus pear) distribution using maximum entropy model (Maxent 3.3.3k).

Table 4. HWSD and ISRIC comparison.

Feature	**HWSD**	**ISRIC (1 km^2)**
Map unit composition	HWSD (v1.21)	HWSD (v1.21+some regional updates like climate)
Grid size	1 km^2	1 km^2
Soil depth	Up to 1 m	Up to 2 m
Textural classes	three (FAO 1988 conventions)	five (SOTER conventions)
Soil attribute per layer	sixteen	twenty
Uncertainty	Not given/ mentioned	Mean+/-STD (standard deviation)/ mentioned
Climate	No	Yes

Source: Batjes (2015).

Data analysis

Model validation

Model accuracy evaluation was conducted to check the predictive performance of Maxent (Groff, 2011). It was determined by means of Receiver Operating Characteristic plots (ROC) (Bourou *et al.*, 2012). From the total presence points, 75 and 25% were used to calibrate and to validate the model respectively, accordingly the ROC was developed. The significance of ROC was computed by Area Under Curve (AUC). AUC values from 0.5 to 1.0. Accordingly, the model performance was ordered based on Thuiller *et al*. (2008) classification (Table 5).

Maxent is among the species distribution models run through using only species presence geographic records and pseudo-absence. Hence, AUC is used to measure model accuracy based on sensitivity and specificity analysis. Sensitivity measures the probability of a real presence points being predicted as a present by the model. However, specificity is the probability of being predicted as pseudo-absence by the model (Phillips *et al*., 2006).

Table 5. Model performance.

Threshold	Remark
>0.90	Excellent
0.80-0.90	Good
0.70-0.80	Acceptable
0.60-0.70	Bad
0.50-0.60	Invalid

The performance of the model was improved by adjusting maximum iteration numbers to 5,000 in order to allow adequate time for convergence. In addition, the model was run for 15 replicates in order to get an average value.

Environment variable contribution

Maxent produced percent contribution and jackknife were used to identify the contribution of each environmental variables for the predicted distribution of each species. Jackknife evaluates the contribution and the unique information of each environmental variable that provides. This was important to reduce multi-co-linearity error (Baldwin, 2009). In addition, response curves were used to show the defining/limiting environmental variables (Buermann *et al*., 2008).

Suitability threshold

In default, Maxent produces a map having from 0 to 1. These values were used to classify habitat suitability (Baldwin, 2009). These values were classified as suitable or unsuitable based on the threshold. Therefore, areas with above 0.3543 are classified as suitable, if not as unsuitable (Table 6).

Table 6. Suitability value.

SN	Value	Classification
01	0.7087-1.0000	Excellent area
02	0.5315-0.7087	Optimal area
03	**0.3543-0.5315**	**Suitable area**
04	0.1772-0.3543	Less suitable area
05	0.0000-0.1772	Unsuitable area

Sources: Reddy *et al*. (2014).

Impact Analysis

One way ANOVA was used to identify whether there were any significant climate change impact, cochineal invasion, and combined effects of climate change and cochineal invasion on future cactus pear distribution.

RESULTS AND DISCUSSION

Current and future climate of the study area

Figure 3 highlights that in the baseline (1980-2009) the temperatures of Ganta Afeshum has been ranged from 6.1 to 24.6ºC with an average annual temperature of 15.4ºC. This will increase to 19.35, 20.40, and 20.70ºC in RCP4.5 near, mid, and end term, respectively, and it will increase to 19.95, 21.10, 22.70ºC in RCP8.5 near, mid, and end term, respectively.

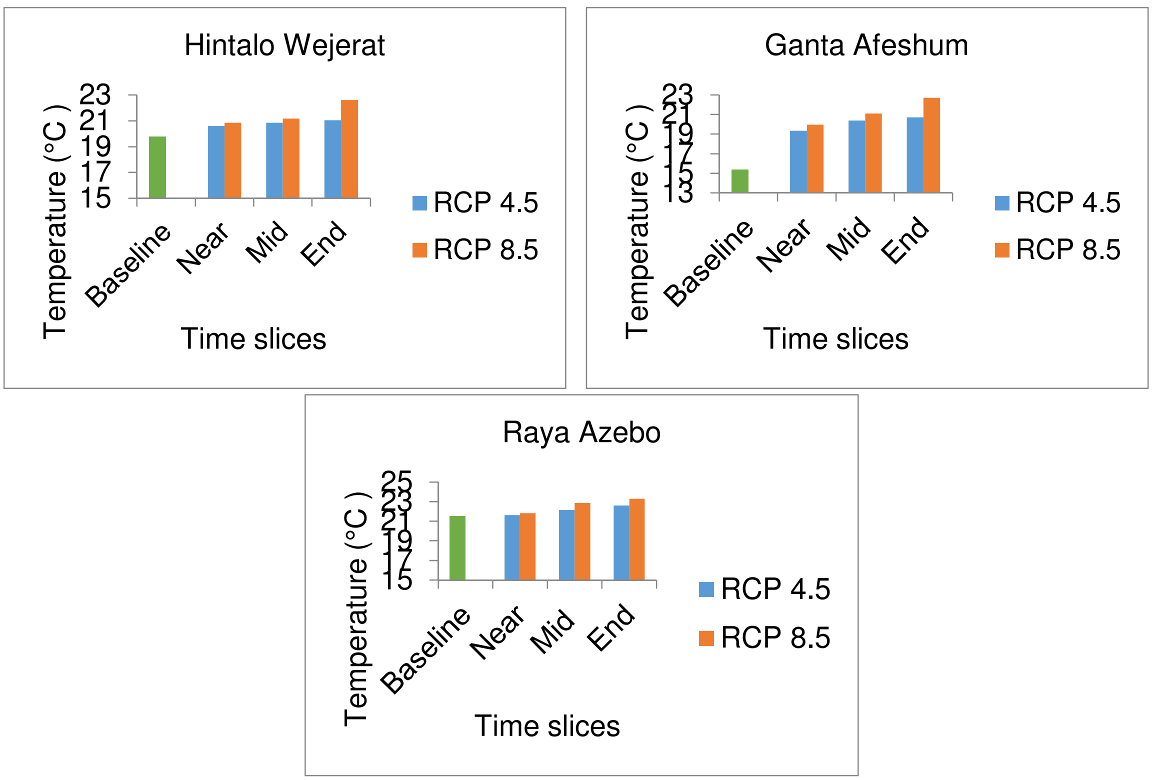

Figure 3. Baseline and projected temperature.

The temperatures of Hintalo Wejerat were also ranged from 13.0 to 26.6°C with an average annual temperature of 19.8°C. This will increase to 20.60, 20.80, 21.04ºC in RCP4.5 near, mid, and end term, respectively, and it will increase to 20.85, 21.20, 22.60ºC in RCP8.5 near, mid, and end term, respectively. Raya Azebo's were also ranged from 14.5 and 28.5°C with an average annual temperature of 21.5°C. This will increase to 21.62, 22.15, 22.62°C in RCP, 4.5 near, mid, and end term, respectively. It will increase to 21.84, 22.90, 23.30ºC in RCP8.5 near, mid, and end term, respectively. In all districts, the projected average temperature for the three districts indicated an increasing trend (Figure 3). The same to this study, McSweeney *et al.* (2010) explained that the average annual temperature of Ethiopia is projected to increase.

In the past thirty years (1980-2009) the average annual rainfall of Hintalo Wejerat was 598 mm. But, this will become to 585, 594, 636 mm in RCP 4.5 near, mid, and end term, respectively, and it will become to 609, 585, 599 in RCP 8.5 near, mid, and end term, respectively (Figure 4).

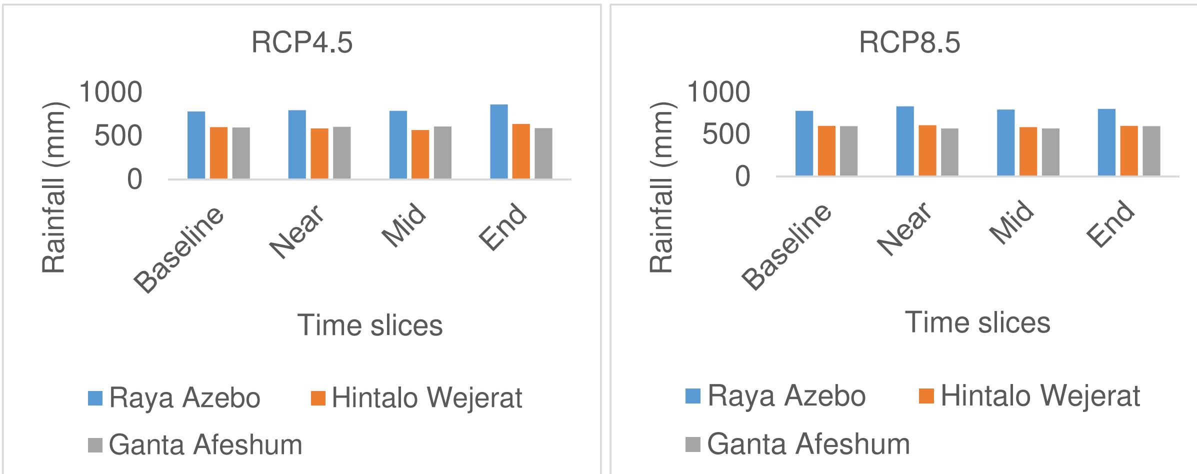

Figure 4. Baseline and projected rainfall.

The rainfall of Ganta Afeshum was also 595 mm. Nevertheless, this will become to 601, 606, 587 mm in RCP 4.5 near, mid, and end term, respectively, and it will become to 570, 570, 594 mm in RCP 8.5 near, mid, and end term, respectively. Raya Azebo's was also 779 mm. This will become to 794, 787, 860 mm in RCP 4.5 near, mid, and end term, respectively, and it will become to 832, 794, 800 mm in RCP 8.5 near, mid, and end term, respectively. In all districts, the projected average rainfall shows that there will be variation (Figure 4). The same to this study, Shongwe *et al.* (2009), indicated that Ethiopian future projections of precipitation are more complex to identify the trend as there is high spatiotemporal variation. In line to this study, rainfall of the study area is distributed unevenly and characterized by large spatial variation that is related with a topographic difference (Gebrehiwot and Veen, 2013).

Climate change impact on cactus pear distribution and cochineal invasion

Model performance

Maxent performance demonstrated excellence for both training and test data of cactus pear distribution and cochineal invasion. From figure 4, the average AUC for training and test value for cactus pear distribution and cochineal invasion were 0.98 and 0.97, respectively, indicating excellent model performance. According to van Zonneveld *et al.* (2009), AUC above 0.9 indicates excellence of model performance. Therefore, the average test AUC was excellent (Figure 5).

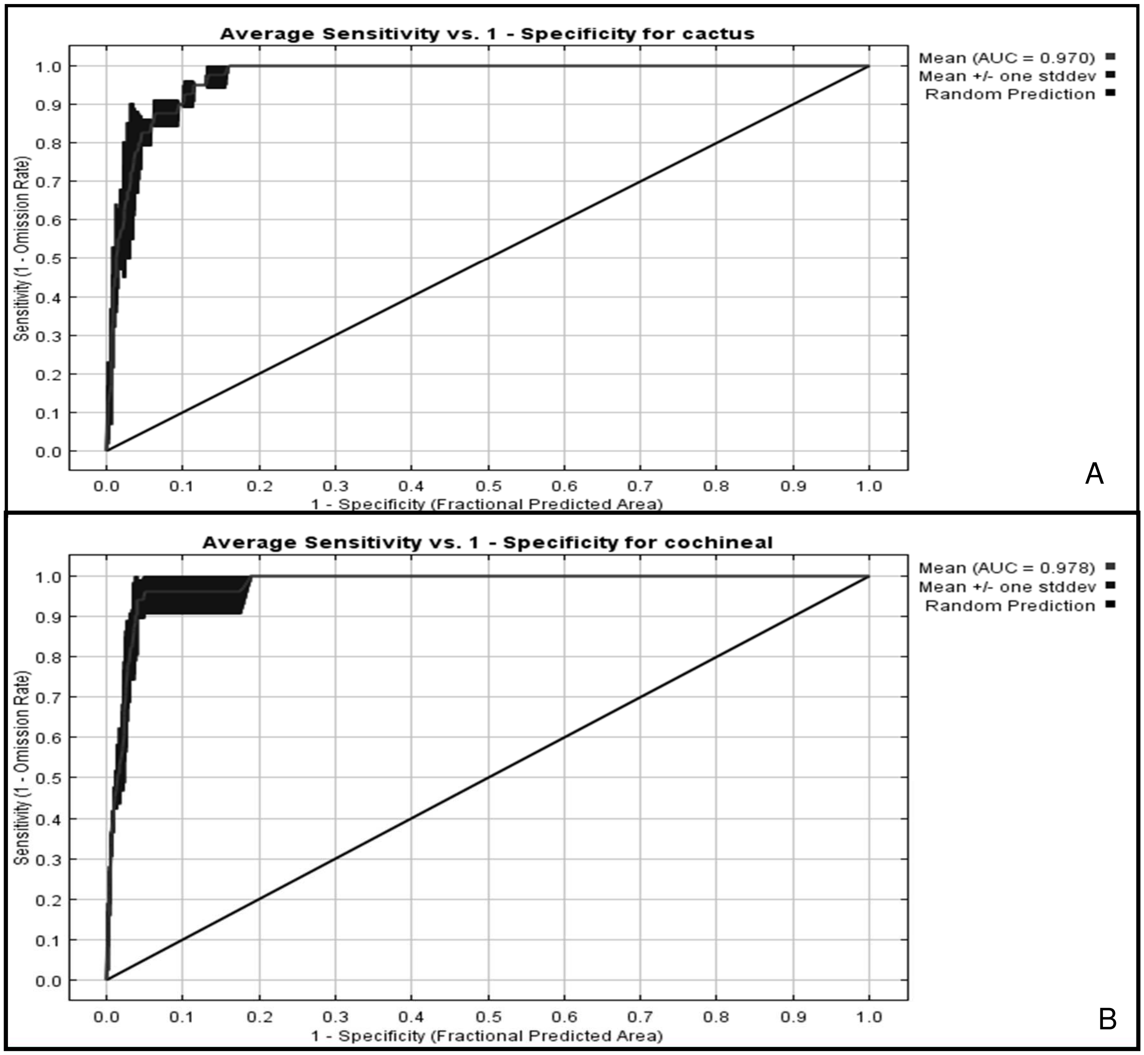

Figure 5. Area under curve, (A) For cactus pear distribution, (B) For cochineal invasion.

Environmental variables used to determine the species distribution

Cactus pear distribution

The result showed that bio 18, bio 19, bio 15, bio 16, and vertisol were top five important environmental variables that explained the cactus pear distribution in that order (Table 7). Bio 18 it has the most useful contribution to cactus pear distribution because it had the highest gain when used in isolation (Table 7).

Table 7. Contribution of variables on cactus pear distribution.

Variable	Percent contribution
bio 18	25.7
bio 19	18.2
bio 15	8.7
bio 16	8.2
vertisol	6.7

According to the response curve of the modeling, the area with maximum temperature 20-30°C is suitable for cactus pear distribution. Its distribution is also suitable when the minimum temperature is between 0 to 5°C and the average annual temperature is between 18 to 24°C (Figure 6).

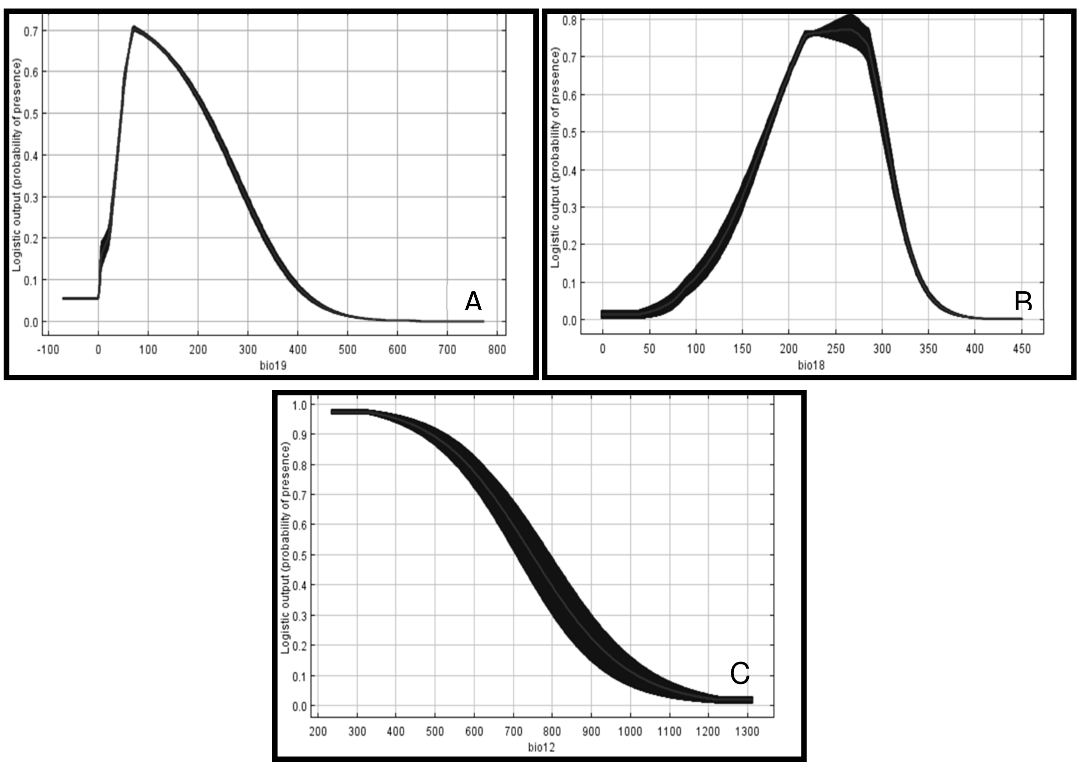

Figure 6. Cactus pear response to variables, (A) precipitation of coldest quarter (Factor 1), (B) precipitation of wettest quarter (Factor 1), (C) annual precipitation (Factor 1).

The precipitation of warmest quarter ranging from 100 to 300 mm was projected to be suitable for cactus pear distribution with the most suitable areas having about 230 mm (Figure 6). Suitable area for the cactus pear distribution is when precipitation of the coldest quarter ranges from 100 to 150 mm and with 350 mm of precipitation in the wettest quarter of a year. The maximum annual rainfall for the species could be about 600 mm. However, the suitability of the species distribution will reduce when total annual rainfall is between 600 to 1,000 mm. The suitability of cactus pear presence is very less when annual precipitation exceeds 1,000 mm (Figure 6). The same to this study, FAO (2013) stated that an average annual rainfall between 200 to 600 mm is suitable for cactus pear. Mondragón-Jacobo and Pérez-González (2001), also revealed that a temperature above 30°C is not suitable for cactus pear.

The study showed that vertisol, cambisol, kastanozem, luvisol, and calcisol are suitable soil types to the cactus pear distribution. Nevertheless, aliosols, fluvisols, stagnosols, regosols, and phaeozems have an indirect relationship with cactus pear distribution. This indicated that as other plant species, cactus pear also selects its suitable soil types. According to De Andrade Ferreira *et al*. (2012), the nutritive quality of cactus pear depends on soil type and climate. Cactus pear chemical contents also vary by soil type variation (El-Mostafa *et al*., 2014). In addition, the yield of cactus pear is differed by soil type (Kriticos *et al*., 2003). Belay (2010) also stated that cactus pear productivity depends on soil type and climate variability. Therefore, soil type is a determinant factor for cactus pear production and distribution.

Cochineal invasion

Cochineal invasion was also affected by both climatic variables and cactus pear presence. Cactus pear (91%), precipitation of coldest quarter (4.40%), annual rainfall (2.60%) and precipitation of warmest quarter (0.50%) were the top four important environmental variables that explain the species invasion ability (Table 8). Cactus pear distribution has the most useful information by itself and contains the most information that is not present in the other environmental variables. Therefore, apart from the climate variables, cactus pear has a high contribution to the invasion of cochineal. In line with the study, Sutherst *et al.* (2011) stated numbers of pest invasion are most highly correlated with their host plants. Rising temperature and rainfall variability are also leading factors that facilitate the invasion of pests (Bebber, 2015). Similar to this study, cactus pear is correlated with cochineal production and development (Karny, 1972).

Table 8. Contribution of variables on cochineal invasion.

Variable	Percent contribution
cactus	91
bio 19	4.4
bio 12	2.6
bio 18	0.5
bio 15	0.4

The suitable maximum temperature of the warmest month for cochineal invasion is between 20 to 40°C. The minimum temperature of the coldest month suitable for cochineal invasion is up to negative 5°C. The annual average temperature ranging from 8 to 24°C is predicted to be suitable for the cochineal invasion. Specifically, an area having annual average temperature of 22°C is suitable condition for the cochineal invasion (Figure 7). Overall, the areas having a temperature from negative 5°C to positive 40°C are suitable areas for cochineal invasion. In line to this study, the standard temperature for cochineal production is 25°C and can withstand a temperature of 45°C for restricted days. Additionally, low temperature causes a retarding effect on the amount of cochineal growth (Karny, 1972).

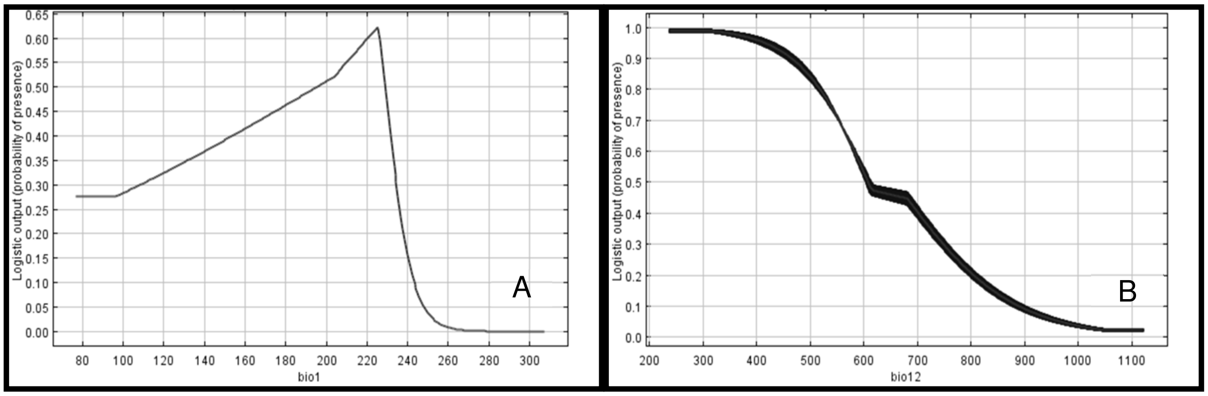

Figure 7. Cochineal response to predictors, (A) annual mean temperature (Factor 10), (B) annual precipitation (Factor 1).

Areas having precipitation of coldest quarter and annual precipitation from 0 to 250 and 250 to 700 mm are suitable for cochineal invasion respectively (Figure 7). Nevertheless, its invasion circumstance will be reduced when mean annual rainfall goes above 700 mm. Therefore, cochineal invaded in both high and low temperature, but its invasion capacity increases safely where mean annual rainfall is below 700 mm. A similar result was reported by Diaz-Cayeros and Jha (2012).

Climate change impact on cactus pear distribution

Figure 8 below highlights that cactus pear distribution will be reduced in the study area under different time slices and RCPs due to precipitation and temperature change. The cactus pear distribution will be reduced by 13, 0.51, and 27% during mid-century RCP 4.5, mid and end-century RCP 8.5, compared with the current. Nevertheless, in end century of RCP 4.5, it will be increased by 0.8%. Overall, the distribution of the species will be reduced when compared with the current. However, climate change impact on the future cactus pear distribution is insignificant (Table 9).

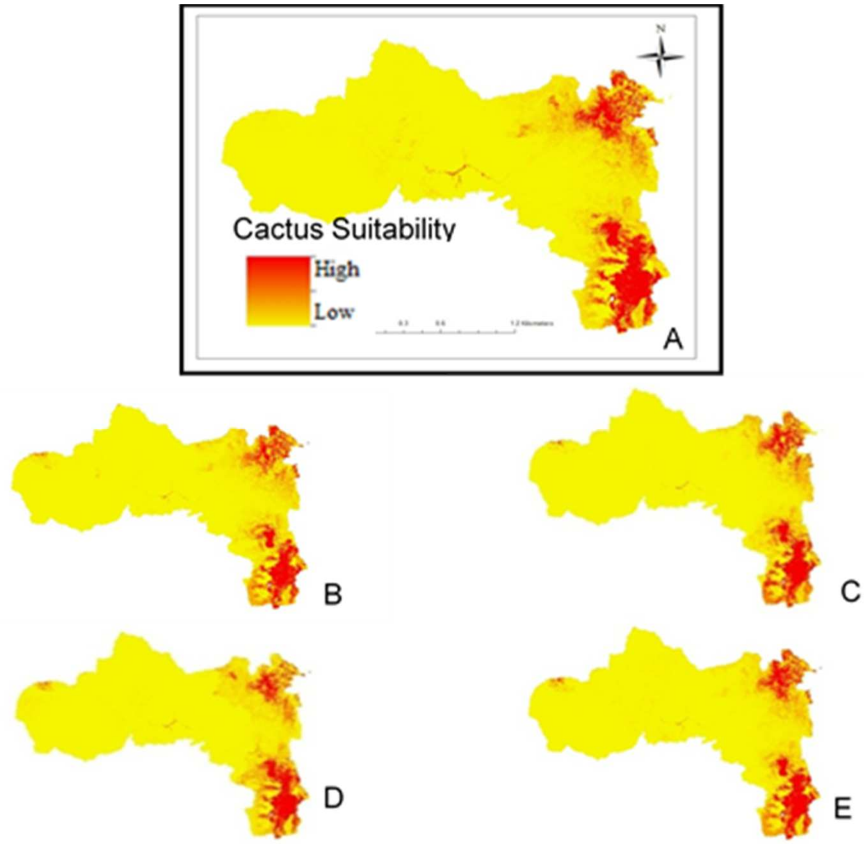

Figure 8. Cactus pear distribution (A) current (1963 km^2), (B) mid-century RCP4.5 (1,712 km^2), (C) mid-century RCP8.5 (1,953 km^2), (D) end century RCP4.5 (1,978 km^2), (E) end of century under RCP8.5 (1,442 km^2).

Table 9. Effects of independent and coupled on future cactus pear distribution.

Effect	Mean difference	P-value
Climate change	153.400	0.145
Cochineal	661.800*	0.000
Coupled	556.600*	0.000

*The mean difference is significant at 0.05 level.

Climate change impact on cochineal invasion

The study finds out that cochineal invasion will be increased. Approximately 61.8% of the current cactus pear resource is affecting by cochineal infestation. Further, it will invade 72, 74, 62, and 94% of cactus pear resources in mid-century RCP 4.5, mid-century RCP 8.5 and end-century RCP 4.5, respectively. In the end-century RCP 8.5, cochineal invasion will be increased by 32.3% when compared with the current. In general, cochineal invasion will be increased in both RCPs and time slices when compared with the current (Figure 9). Therefore, it will have a significant impact on future cactus pear distribution (Table 9).

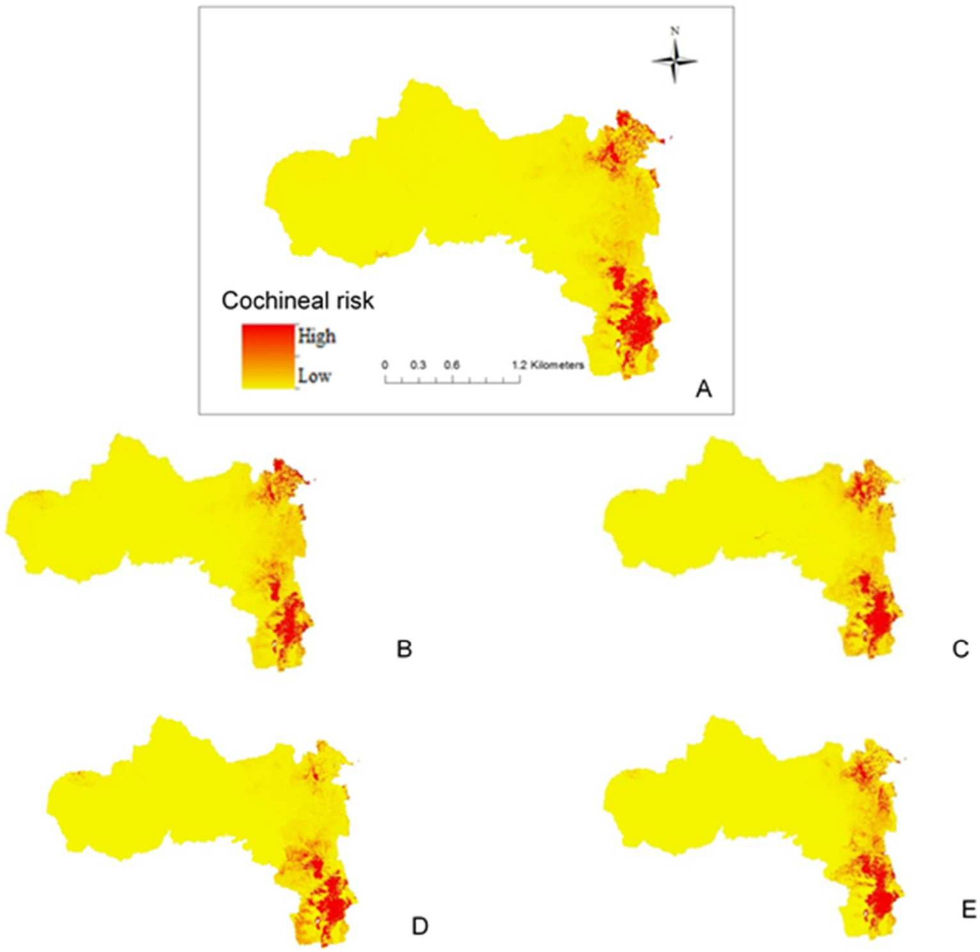

Figure 9. Cochineal invasion risk, (A) current (1213 km^2), (B) mid-century RCP4.5 (1263 km^2), (C) mid-century RCP8.5 (1443 km^2), (D) end-century RCP4.5 (1230 km^2), and (E) end-century RCP8.5 (1357 km^2).

Combined effects of cochineal invasion and climate change on future cactus pear distribution

The combined effect of climate change and cochineal invasion will affect 72, 78, 63, and 85% of cactus pear resources during mid and end-century of RCP4.5 and RCP8.5, respectively. During end-century of RCP4.5, the cactus pear distribution will be affected by only cochineal invasion; while there will be no climate change effect on cactus pear distribution (Figures 10). Overall, it will have a significant impact on future cactus pear distribution (Table 9). According to Ayres and Lombardero (2000), both climate change and pest invasion affect plant life. In addition, temperature increment and moisture variation are the main causes of pest invasion (Hellmann *et al*., 2008).

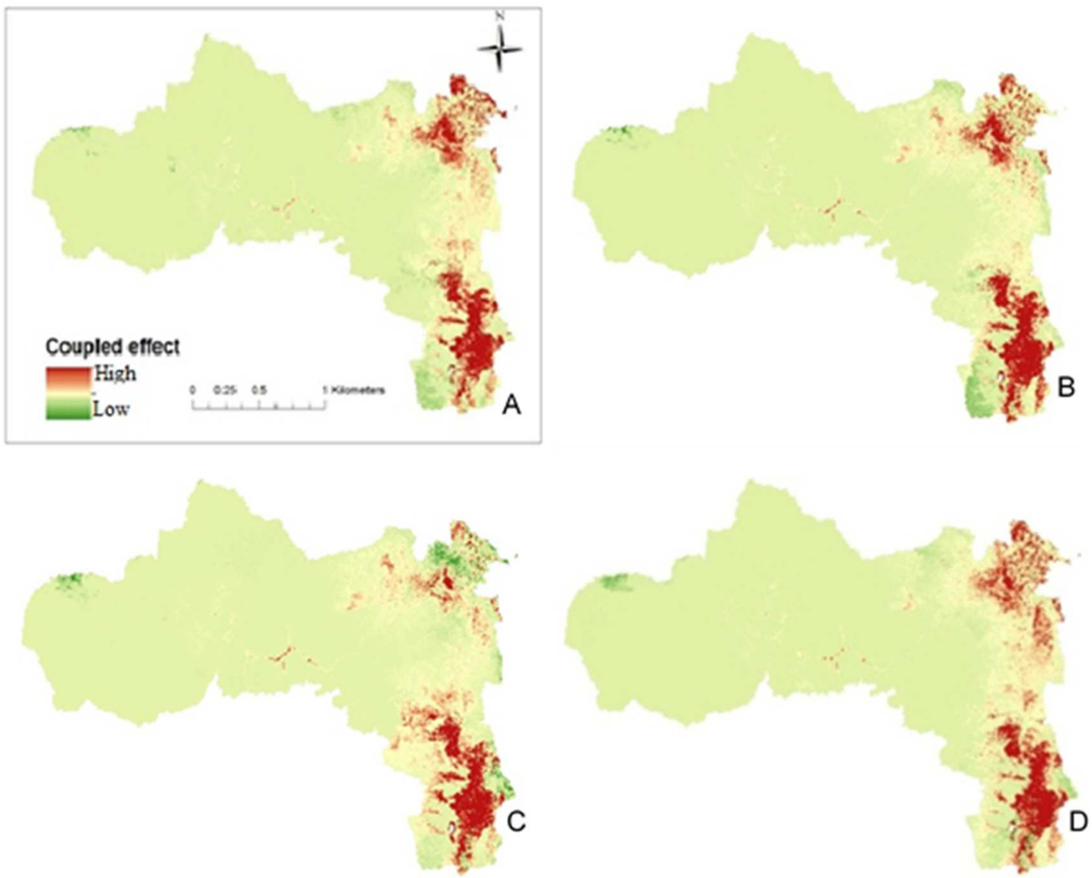

Figure 10. Combined effect of cochineal invasion and climate change on cactus pear distribution, (A) mid-century RCP4.5 (1401 km^2), (B) mid-century RCP8.5 (1530 km^2), (C) end century RCP4.5 (1230 km^2), (D) end century RCP8.5 (1658 km^2).

Overall, the distribution of cactus pear will be reduced due to the coupled effect of cochineal invasion and climate change more than what would happen in isolation. Hellmann (2008) and Dukes (2009) have found similar findings.

CONCLUSIONS

In the study area, cactus pear distribution will be decreased because of climate change and cochineal invasion.

Cactus pear presence has 91% contribution on cochineal invasion and the remaining 9% are climatic variables. Due to this reason, it invades almost all cactus pear resources of the study area. In addition to the independent effects of cochineal invasion and climate change, their combined effects will also contribute to the reduction of cactus pear distribution.

Overall, climate change will pose an insignificant impact on the future cactus pear distribution. However, the combined effects of both climate change and cochineal invasion will have a significant impact on future cactus pear distribution.

IMPLICATIONS

Therefore, the study recommends that future cactus pear potential of the area will reduce due to both cochineal invasion and climate change impacts. As the result, adaptation measures should be taken. For example, the socioeconomic dependency of the society on cactus pear should be replaced gradually to other drought-resistant crops. Cactus pear is threatened species, especially by cochineal invasion. It is important to target management interventions (biological method) to control the cochineal invasion. Otherwise, it is better to change into valuable products in such a way both the cactus pear and the cochineal can be utilized under intensive management.

There are only old/ fewer research reports on the type of cactus pear, pests, time of occurrence, duration of the pest occurs, level of severity in which the insects attack the plant. Hence, a similar study should be carried out considering other factors to develop a robust result. An international trade like cochineal rearing is difficult without environmental impact assessment; there should be a prior study on the side effects of imported pests and plants to the country. Additionally, chemical controls which could greatly impact the spread of cochineal like, Platinum (Thiamethoxam) soil applied, Sivanto (flupyradifurone) soil-applied (but not foliar), and Beleaf (Flonicamid) foliar applied should be applied without affecting other beneficial insects such as bee (USDA, Department of Agriculture, IR4 program).

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