CLIMATE CHANGE AND THE AGRICULTURAL POTENTIAL OF SELECTED LEGUME CROPS IN EAST AFRICA

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ABSTRACT

Land expansion to increase agricultural production in East Africa (Burundi, Ethiopia, Kenya, Rwanda, Tanzania and Uganda) will be limited by climate change. In this study, we predict landscape suitability for chickpea (*Cicer arietinum)*, common bean (*Phaseolus vulgaris*), lentil (*Lens culinaris*), field pea (*Pisum sativum*) and pigeon pea (*Cajanus cajan*) cultivated across diverse agro-ecological zones (AEZs) in East Africa from 1970 to 2070, under the 4.5 emission scenario. We aimed to understand how suitability shifts among the AEZs might affect the agricultural potential of the selected crops. We use the geolocations of each crop together with response curves from the species distribution software, Maxent to fine-tune the expert-based EcoCrop model to the prevailing climatic conditions in the study region.

Our optimal precipitation and temperature ranges compared reasonably with the FAO base parameters, deviating by ±200mm and ±5°C, respectively. There is currently a high potential for lentil, pea and common bean in the region. However, under future climates, the suitability of common bean and lentil with a much narrow climate range will shrink considerably while pigeon pea and chickpea will continue to be suitable. Under projected climatic conditions, the agricultural potential of these legumes will be limited by drought or heat stress as landscape suitability will shift optimally toward the cool sub-humid (tcsh), and the cool semi-arid (tcsa) zones. Tanzania, Kenya and Uganda will be the most affected and will lose a large share of suitable arable land.

Different adaptation measures will be needed to increase the agricultural potential and optimized production in vulnerable AEZs. In general, smallholder farmers will have to substitute lentil and common bean for chickpea and pigeon pea or other suitable substitutes to address food security issues. Notwithstanding the limitations of this study, our results highlight the vulnerability of legumes crops as well as their production zones which could be useful in the formulation of adaptation strategies for the East African region.

Keywords: *climate change, EcoCrop, legumes, agro-ecological zone, East Africa.*

INTRODUCTION

Legumes are dominantly produced and consumed in East Africa as dry seed (pulses)[1]. Production is, however, constrained by soil degradation and most importantly, by changing climatic conditions [2], [3], [4]. Climate is important among other factors because more than 90% of agriculture production in the region is rain-fed [5]. Precipitation combined with temperature determines the length of the growing season (LGS) as well as the planting dates[6], [7]. On the other hand, temperature regulates metabolic processes, while the interaction of both factors within their optimal ranges is a prerequisite to optimize growth and yield [5]. While the optimal climate ranges for more than 2500 plant species have been well documented by the United Nations Food and Agricultural Organization (FAO), through its EcoCrop database, the climate ranges for some crops and regions are yet to be validated.

Climate projections show that the East African region will warm between 2 - 6^{o}C on average, while precipitation by the year 2100 will generally increase, for the high (RCP 8.5) emission scenario [8]. However, the intensity of rainfall in the region is still debatable among climate experts because of the complex topography and monsoons of the region which cannot be adequately captured by global climate models (GCM) [3], [9]. Such changing climatic conditions is already having a noticeable impact on the agricultural sector. For example, in West Africa, [6], found that changes in precipitation patterns might delay future planting months of seasonal crops. In the face of changing climatic conditions, crops that can adapt to very narrow climate ranges are usually the most affected [10], [11], [12]. Predictions from crop suitability and crop yield models have consistently reported a spatial shift in landscape suitability of vulnerable crops, mainly from lowland to highlands in the near or distant future [4], [13]. Although the shift in suitability is well recognised, there is also a need to understand how such variations will affect the agricultural potential of these legumes in East Africa because (i) legume cultivation in the region is done across diverse agro-ecological zone (AEZs), with different levels of vulnerability to climate change [7], [13] and (ii) current production is somehow selective with countries such Tanzania and Uganda dominantly focusing on one legume crop type - common bean (FAO). Common bean has been well researched and is known to be a vulnerable crop [11], [12] however, legumes such lentil, field pea and chickpea remained under-researched [10]. Understanding how landscape suitability will change for each of these legumes in the near distant future is probably the first step required to plan adaptation strategies to address food security issues in the region.

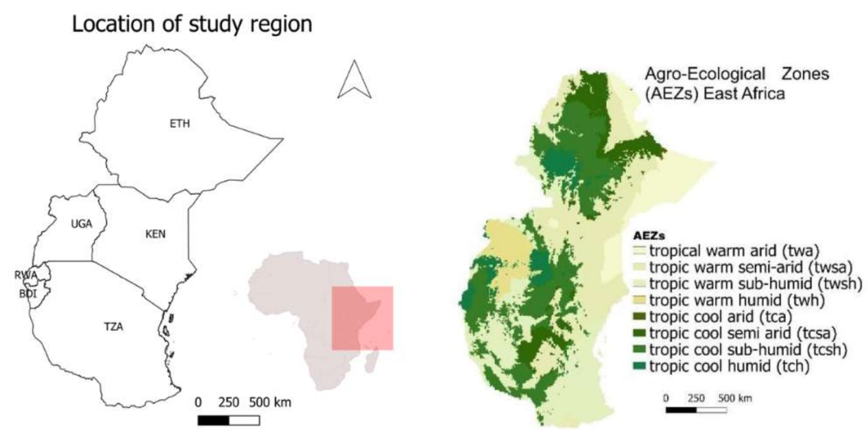
OBJECTIVES

This study aimed at analysing the impact of future climate on the agricultural potential of selected legumes cultivated in East Africa. Our objective was to predict possible shifts in agro-ecological zones and their impact on the agricultural potential of the selected crops. We attempt to achieve this goal by adjusting the input parameter for the expert-based EcoCrop model [14], [15] to the prevailing climatic conditions in East Africa using the geolocations of each crop.

Study Region

The study region includes Ethiopia, Tanzania, Kenya, Uganda, Rwanda and Burundi (Fig 1a). The region's landscape is heterogeneous and characterised by rifts valleys lakes and highlands. Annual precipitation in most of the region varies from 800 to 1200mm, with more rainfall in mountainous and lake regions [15]. The rainy season varies from March to May (MAM) for long rains, June to August (JAS) and October to November (ON) for short rains. However, most of the tropical parts experience both the MAM and the ON rainy seasons per year [15].

The legume crops considered in this study include chickpea *(Cicer arietinum)*, lentils *(Lens culinaris)*, beans (*Phaseolus vulgaris*), dry pea *(Pisum sativum*) and pigeon pea (*Cajanus cajan*). These crops thrive in cool environments and are commonly grown on together with maize, millet, sorghum cassava and groundnuts [3], [16]. Figure 1b show the major AEZs of the study region, which differs in their availability of moisture, temperature and other resources for plant growth [7].



a) *b)*

Figure 1: (a) Location of the study region and (b) Agro-ecological zone in the study region *(adapted from HarvestChoice 2009)*

Precipitation and temperature during the growing season for common bean vary from 200 to 1100mm and from 15 to 25, respectively [3], [16]. Chickpea is generally sown in Late September and depends more on residual moisture to complete its growth cycles [2], [16], [17]. It requires 78 to 380mm 16 to 21°C of moisture and temperature respective during its growing season [1], [2], [16]. Lentils, unlike chickpea, are severely affected at temperatures above 27°C and grow optimally within the temperature range from 18 to 21°C and precipitation from 350 -550mm [17]. Dry pea in Ethiopia is commonly grown from July to December and require 800 to 1000mm and 10 $^{\circ}$C to 27°C of rainfall and temperature [17]. Pigeon pea is more drought-tolerant than bean, lentil and chickpea and requires from 250mm to 800mm and 17 $^{\circ}$C to 35°C of Precipitation and temperature respectively during its growing season [1], [16], [17].

METHODOLOGY AND DATA

We proceed as follows. First, we acquire crop location datasets, climate dataset, agricultural land dataset and agro-ecological zone dataset of the study region. Next, we calibrate and evaluate model parameters and analysed crop distribution and suitability modeling using Maxent [18] and EcoCrop software, respectively. Lastly, we analyse model output, integrate the best model results with agricultural and agro-ecological zone datasets of the region and compare our results with those from existing studies in the region. The methodology we followed is summarized in Fig 2 while Table 1 presents a summary of these datasets

Crop Occurrence

Evidence of pea, chickpea, pigeon pea, beans and lentils occurrence from 1960 to 2017 were obtained from the Plant Genetic Resources for Food and Agriculture (Genesys portal https://www.genesys-pgr.org) and from the website of the Global Biodiversity Information Facility (GBIF portal, https://www.gbif.org). We use evidence data for this time range to get enough geolocations because legume data for most of the region is rare [1]. These datasets were processed, by checking and removing duplicate points to reduce sampling bias, removing missing or completely absent coordinate as well as misrepresented coordinates. Thus, the processed sample size for bean = 685, chickpea = 694, lentil= 249, pea=394 and pigeon pea =315. Figure 2 shows the locations of production sites of legume crops in the study region.

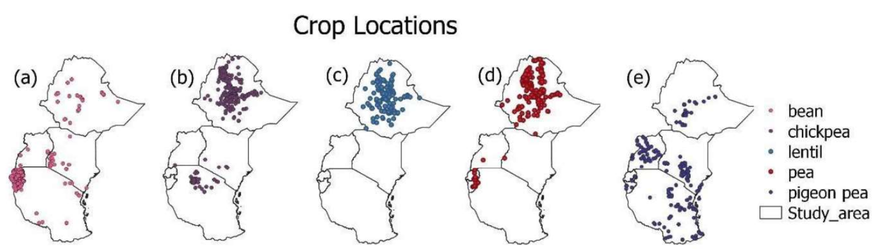


Figure 2: Crop locations (a) common bean, (b)chickpea, (c)lentil, (d) pea (e) pigeon pea

Climate Dataset

We obtained long-term averages of historical climate datasets at 30-second arc resolution (~1km at the equator) from 1970 to 2000 (also referred to as "current climate") and future climate data for the year 2070 from www.worldclim.org [19]. The future climate datasets are calibrated outputs from Global Climate Models (GCMs) of phase 5 of the Coupled Model Inter-comparison Project (CMIP5) on which the 5th assessment report of the intergovernmental panel on climate change (IPCC5) is based. In this study, we used the mean ensemble (on a pixel basis) of 4 GCMs for RCP 4.5. The 4 GCMs included: ACCESS 1-0, CCSM4, HadGEM-ES and NorESM1-M.

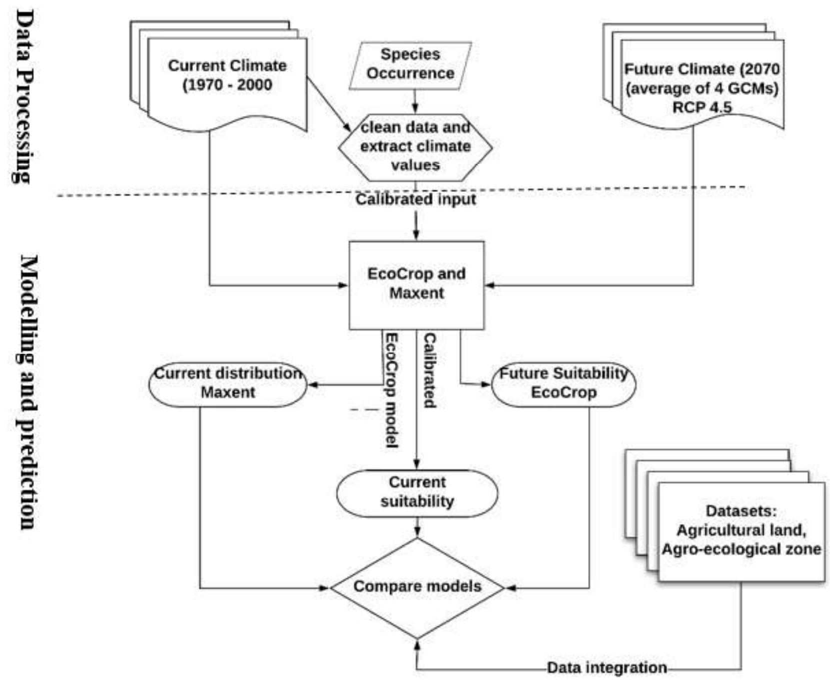


Figure 2: Methodology and conceptualisation of workflow

Table 1: Summary of data sources

Data	Source(s)	Resolution
Climate	WorldClim.org	30 sec arc
Crop locations	Genesys, https://www.genesys-pgr.org/	
	GBIF, https://www.gbif.org/	
Agro-Ecological Zones (AEZs)	HarvestChoice/International Food Policy Research Institute (IFPRI) https://harvestchoice.org/data/aez8_clas	5 min arc
Agricultural land	SEDAC, http://sedac.ciesin.columbia.edu/es/aglands.html	5 min arc

Spatial Modelling

Before spatial modelling, we respectively use 70%, and 30% of each crop together with the default background sample size to train and validate the spatial distribution of each crop in Maxent software. We use two or more of following bioclimatic variables (predictors) directly related to plant growth as predictors: Bio10 (Mean Temperature of Warmest Quarter), Bio11 (Mean Temperature of

Coldest Quarter), Bio12 Annual Precipitation), Bio16 (Precipitation of Wettest Quarter) and Bio17(Precipitation of Driest Quarter).

We modelled the suitability of each crop for the current and future climate using EcoCrop [14], [15]. EcoCrop predicts suitability on a pixel basis by comparing the specific temperatures and precipitation ranges of a crop with prevailing condition elsewhere. The model scores suitability on a scale of '0' (for unsuitable areas) to '1' (for excellently suitable areas) depending on the climate range of the crop. The implementation of EcoCrop in GIS softwares is always supported by the EcoCrop database documenting the base biophysical parameter of more than 2500 plant species. These biophysical parameters may be too generic depending on or crop type or the scale of the study.

Model Calibration and Evaluation

To calibrated and evaluated model parameters; we use the geometric mean of the growing season. From the growing season, we created two fictitious growing seasons for mean temperature and total precipitation from (equation 1 & 2) respectively. Each of the false growing seasons had 12 consecutive sequences of four months for chickpea, lentil, common beans and six months for pigeon pea. For field pea with a growing season of 3 months, we use the quarterly bioclimatic variable (BIO10, BIO11, BIO16 and BIO12) from worldclim.org and extracted their values from each point.

$$T_{GS} = \frac{1}{4}\left(\sum_{i=1}^{i=4} t_{\mathrm{avg}_i}, \sum_{i=2}^{i=5} t_{\mathrm{avg}_i}, \ldots, \sum_{i=12}^{i=3} t_{\mathrm{avg}_i}\right) \quad (1)$$

$$R_{GS} = \left(\sum_{i=1}^{i=4} r_{\mathrm{sum}_i}, \sum_{i=2}^{i=5} r_{\mathrm{sum}_i}, \ldots, \sum_{i=12}^{i=3} r_{\mathrm{sum}_i}\right) \quad (2)$$

Where $\mathbf{i}$ represents the month(s), the mean temperature($\mathbf{t}_{\mathrm{avgi}}$) for 12 consecutive growing seasons ($\mathbf{T}_{\mathbf{GS}}$), has four consecutive months per season. The total rainfall ($\mathbf{r}_{\mathrm{sumi}}$) for 12 consecutive growing seasons ($\mathbf{R}_{\mathbf{GS}}$) has four consecutive months per growing season

From the 12 potential growing seasons, we choose the sequence with the lowest and highest mean temperature to calibrate temperature inputs. For precipitation, we selected the sequence with the highest sum of rainfall to ensure enough moisture during the growing season. For each crop locations, we then extracted the current temperature, and precipitation values from these sequences and adapted the approach of [14] to determine EcoCrop model input. To further fine-tune model inputs, we compare the optimum temperature and precipitation values with those from existing field studies as well as with the results of response curves of the main predictors in Maxent. Thus, we use the precipitation range of pea as a proxy for bean because both crops have nearly the same precipitation but slight different temperature requirement [17], (FAO). Moreover, the range equally compares with field values for the study region [16]. For pigeon pea, we used annual precipitation to derive its optimal and marginal precipitation inputs because annual rainfall was a significant predictor in Maxent. Secondly, pigeon pea has a very long growing season. Table 1 summarizes the input parameters used to drive EcoCrop

RESULTS

We present and evaluate the calibrated temperature, and precipitation ranges for each crop as well as changes in suitability across agro-ecological zones.

Crop climate niche

Figure 4a and 4b show the variation in annual precipitation against the mean annual temperature of the selected crops.

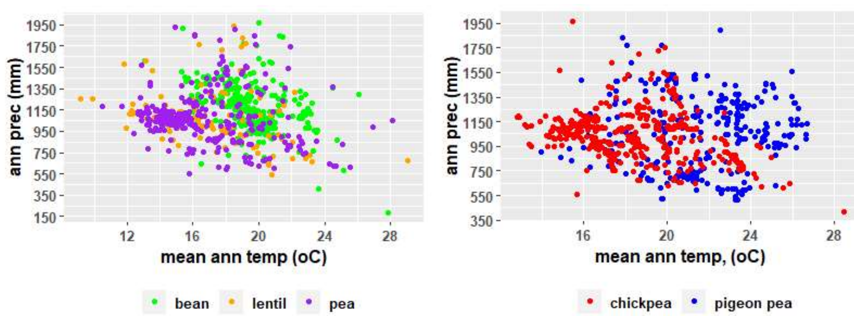


Figure 3: Annual temperature and precipitation range of the chosen crops (a) bean, lentil and pea (b) chickpea and pigeon pea

Generally, rainfall and temperature at production sites vary from 550 to 1550mm and from 8°C to 29°C respectively and roughly reflects each crop's climate niche. In Fig 4a most pea, bean and lentil-growing areas receive almost the same amount of precipitation per year. However, the mean annual temperature for lentil and pea production sites range from 13 °C to about 19 °C while in bean growing areas, it varies from 16 °C to 22 °C. In Fig 4b, the mean annual temperature range for chickpea and pigeon pea locations are almost the same. However, the temperature range for most chickpea locations varies from 12 °C to 25°C compared to 20°C to 27°C for pigeon pea. These differences in temperature precipitation range broadly show some differences in adaptation to climatic conditions

Model calibration and evaluation

Table 2 shows the calibrated model parameters used to drive EcoCrop. These parameters are presented together with the FAO base parameter for comparison. Generally, the calibrated temperature inputs for all crops except for pea were 3 to 5 degrees lower than the based parameter. All calibrated optimum minimum precipitation (RopMn) were ~50 to 100mm less than base except for pea. While the optimum max precipitation for all crops except for common bean was 150 to 200mm higher than the FAO base input.

Table 2: Comparison of calibrated inputs with FAO base parameter

	LGS (days)	Tkill (°C)	Tmn (°C)	TopMn (°C)	TopMx (°C)	Tmx (°C)	Rmn (mm)	RopMn (mm)	RopMx (mm)	Rmx (mm)
Bean	90	0	10	15	20	27	151	452	1054	1355
FAO base	160	0	7	16	25	32	300	500	2000	4300
Chickpea	120	0.85	3.4	10.2	24	31	182	547	1274	1638
FAO base	135	-9	7	15	29	35	300	600	1000	1800
Lentil	120	0.75	3	9	21	27	167	506	1180	1517
FAO base	155	0	5	15	29	32	250	600	1000	2500
Pea	90	0.82	3.3	9.9	23.1	29.7	151	452	1054	1355
FAO base	100	-2	4	10	24	30	350	800	1200	2500
Pigeon pea	180	1.1	5	14.1	33	42.3	220	658	1537	1976
FAO base	228	0	10	18	38	45	400	600	1500	4000

Where: Rmx= maximum rainfall, RopMx= optimum maximum rainfall, RopMn= optimum minimum rainfall, Rmn= minimum rainfall, Tmx= maximum temperature, TopMx=maximum optimum temperature, TopMn= optimum minimum temperature, Tmn= minimum temperature, Tkill= temperature that will kill the crop and LGS = length of the growing season

Table 2 also shows that Field pea has the lowest moisture requirement (Rmn) while pigeon pea and chickpea have the highest maximum temperature (Tmx). Compare to the base input, Table 2, equally shows that the FAO based maximum precipitation have largely been overestimated at least for the study region. Notwithstanding, the calibrated model inputs are reasonably within the ranges for each crop.

Table 3 shows the proportion of crop locations which fall within the EcoCrop suitability threshold of ≥ 41% or a higher threshold of ≥60%. Table 3 shows that increasing threshold reduces prediction rate by 5% for bean, pea and pigeon pea except for lentil and chickpea. Based on the area under the receiver operating curve (AUC), Table 3 also shows that Maxent model performance for each crop was within the acceptable range [18] although its thresholds and statistical approach is different from Ecocrop.

Table 3: Model prediction rate in Maxent and EcoCrop

	EcoCrop				**Maxent**
	Threshold		Threshold		AUC Value
Bean	0.41	0.68	0.60	0.53	0.90
Chickpea	0.41	0.97	0.60	0.96	0.86
Lentil	0.41	0.89	0.60	0.88	0.89
Pea	0.41	0.83	0.60	0.77	0.91
Pigeon pea	0.41	0.71	0.60	0.64	0.75

Crop Suitability.

Figure 5a – 5e shows the current suitability pattern for each crop. The figure shows that that suitability of chickpea (Fig 5d) and pigeon pea (Fig 5e) is homogeneous compared to a heterogeneous pattern for common bean, lentil and pea and reflect the vulnerability of the later. Generally, there is currently a high potential for all the selected legumes in the study region.

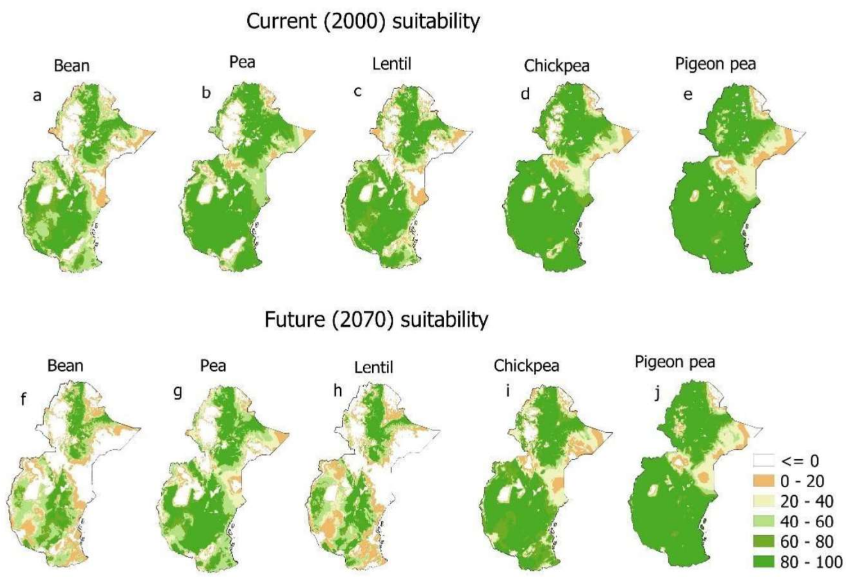
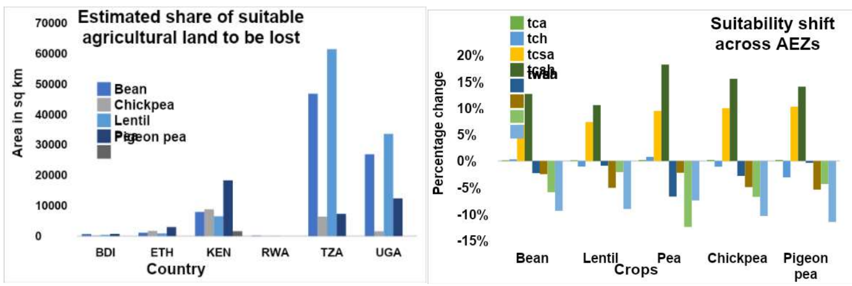


Figure 4:Suitability of legume crops, (a - e) current suitability, (f – j) future suitability

Under future climatic conditions (Fig 5f to 5j), there will be more variability in the suitability of common bean (Fig 5f,) and lentil (Fig 5h) compared to pea, chickpea and pigeon pea. There will also be a significant contraction in the share of suitable areas for common bean and lentil compared to chickpea and pigeon pea which will remain unchanged, thus reflecting the broad climate range and adaptability of the later.

At the country level, Figure 6a shows the estimated share of suitable agricultural land that could be lost (total lost minus total gained) for each country. Approximately 61,000 and 33,000 km^2 share of suitable arable land for common bean, lentil will be lost in Tanzania and Uganda, respectively. Most of the suitable agricultural land in Ethiopia will remain suitable, although the share of suitable land for pea cultivation will reduce. There will be little or no loss of suitable land in Rwanda.

Across AEZs, Figure 6b shows that under future climatic conditions, the most optimal zones for legume cultivation will be the cool humid (tch) the cool semi-arid (tcsa) and the cool sub-humid (tcsh) zones. Suitability within these zones will increase by 10% and 15% respectively and will be most favourable field pea cultivation. Within the warm AEZs, the warm sub-humid (twsh) and the warm semi-arid (twsa) zones will be the most impacted, decreasing suitability at all production sites. Generally, land suitability for, pea will be most reduced in the warm semi-arid (twsa) and the warm (twa) arid zone compared to other crops. The suitability of lentil, chickpea and pigeon pean will be more reduced in the warm humid (twh) zone compared to common bean and pea. The cool humid (tch) zones and cool arid (tca) zones will be negligibly affected.



a) ***b)***

Figure 5. (a) estimated share of suitable arable land that could be lost (b) suitability shift across AEZs. *The share of suitable land in each country is based on an overlay with agricultural land, which is cropland + pastureland. In Fig 3b, tca = tropic cool arid, tch= tropic cool humid, tcsa= tropical cool semi-arid, tcsh=tropic cool sub-humid, twa= tropic warm arid, twh= tropic warm humid, twsa= tropic warm semi-arid, twsh=tropic warm sub-humid.*

DISCUSSION

Climate data and crop suitability

Under baseline conditions, we observe an overlap in the climate range of selected legumes (Fig 4a and 4b) which implies that they can easily substitute each other. Lentil and pea have the same climate niche but differ from common bean, which has a slightly higher temperature requirement in agreement with [17]. The fact that our optimal temperature and precipitation range compared reasonably with the FAO base input (Table 2), although deviating by ±200mm and ±5°C, respectively, suggest that the approach could be promising for other crops. We also observe some deviations in optimal *precipitation* from field studies which could be attributed to the fact field studies tend to be very localized and not representative of the entire region. Thus low prediction rate of ~68% for common bean even after calibration may have been due to sampling not being adequate to represent its full climate range. However, our results show that beside Ethiopia and to a lesser extent Kenya, there is currently a high potential for lentil and field pea production in Burundi, Rwanda, Uganda and Tanzania which appear to be neglected. Smallholder farmers in these countries could take advantage to diversify crops while climatic conditions are still favourable.

Under future climates, we observe (not presented) that there will be more precipitation in most parts of the study region by 2070. The average temperature will increase by ~2.7°C in agreement with existing studies, [8]. These legumes will adapt differently to changing climatic conditions. Pigeon pea and chickpea with broadest climate range will be the most adaptable crop (Fig 5j and 5i) while common bean and lentil will be the least. While these results are similar to existing studies [2], [4], we equally acknowledge the uncertainty of these predictions due to the inherent uncertain in our climate datasets and notably in the rainfall patterns of East Africa [9].

Climate impact on land suitability

By integrating both the agro-ecological zone and agricultural land dataset to the output from EcoCrop model, we had a better assessment of the impact of climate change. The shift in suitability among the agro-ecological zones also reflects the dominant stress factor limiting crop suitability in each zone. Generally, heat will be the dominant stress factor reducing crop suitability in the future, as reported by [4]. The impact of heat stress is based on the fact that suitability either increase or nearly remain constant in the cool agro-ecological zones as opposed to the warm AEZs. In addition to heat stress drought will equally be a limiting factor, especially in the warm semi-arid zones (twsa) and will significantly reduce the agricultural potential of field pea. Excessive moisture, in addition to heat stress in the warm humid zones (twh), will be the limiting factor affecting lentil, chickpea and pigeon production [17].

The impact of climatic change, on landscape suitability for each of these countries, will also largely depend on which AZE dominates. The share of suitable land for common bean and lentil cultivation in Uganda, Kenya and Tanzania will shrink considerably because a large share of the arable land in these countries are within the warm sub-humid (twsh) and the warm semi-arid (twsa) zones. Most of the agricultural land in Burundi, Rwanda and Ethiopia with a more stable cool sub-humid and cool semi-arid conditions will continue to be suitable. Although suitability will generally decrease for all crops and each of these countries, chickpea and pigeon pea being the most resistant to drought [2], [16], (Fig 6d and 6e) or climatic variation will continue to be suitable in the warmer AEZs.

The decreasing suitability of the warm AEZs will also imply that different adaption measures will be needed to increase the agricultural potential of the region optimize legume production in future. For example, shortening crop cycles by delaying planting dates or months [6] will be ideal for the warm sub-humid zones while switching to more drought-tolerant legume variety could be a workable solution for the warm semi-arid zones [2]. Generally, Chickpea and pigeon pea together with other suitable substitutes [12] will be future crops for the region.

It is worth noting that our assessment of the possible impact of climate change on the agricultural potential of the region is based on a much coarser dataset at 5 minutes' degree for the agro-ecological zone and the agricultural land. Hence, we may have missed spatial variability at the country level. Secondly, we must stress that the climate dataset used in this study is based on long term averages of GCMs which may not have adequately capture precipitation pattern in East Africa [3], [8],

[9]. Moreover, we did not analyse seasonal or inter-annual variability, which could equally be helpful for detail assessment especial of the fragile AEZs. These considerations will be necessary to improve these results.

CONCLUSION

In this study, we have attempted to predict and quantify the impact of climate change by 2070 on five commonly grown legumes (field pea, chickpea, lentil, common bean and pigeon pea) in East Africa (Burundi, Ethiopia, Kenya, Rwanda, Tanzania and Uganda). The approach we follow builds on the work of [14] who successfully validated the generic EcoCrop model input parameter for sorghum. We use the geolocations of crops together with response curves from the species distribution software, Maxent to fine-tune the crop suitability model, EcoCrop model to the prevailing climatic conditions in the study region. We found that our calibrated optimal temperature and precipitation ranges compared reasonably with the FAO base parameters, deviating by ±200mm and ±5°C, respectively. Our prediction rate based on suitability range of EcoCrop varied from~70 to 90% and implied that the approach could be useful for other crops. There is, however, a need to improve the calibrated parameters, especially of common bean using more representative datasets.

Notwithstanding, there is currently a high potential for lentil and field pea production in Tanzania, Rwanda and Kenya, which appears to be neglected. Farmers from these countries can take advantage of this opportunity to diversify production while climatic conditions in the region are still favourable. As most of the region warm-ups and also receive much precipitation by 2070, suitability across agro-ecological zones will shift towards the cool zones. The most optimal of which will be cool sub-humid (tcsh) and cool semi-arid (tcsa) zones, highlighting the fact that heat stress will be a major factor limiting legume suitability in the future. Drought and waterlogging may equally be limit factors, especially in semi-arid and sub-mid agro-ecological zones. Different adaption measured will be needed to optimize the agricultural potential of the most vulnerable AEZs. Generally, smallholder farmers will have to substitute bean, lentil and pea with pigeon pea and chickpea or with other drought-resistant crops.

The impact of climate change will be different among the six countries considered. Generally, Tanzania, Kenya and Uganda with a considerable share of warm sub-humid or warm semi-arid arable land will be the most affected. Ethiopia and Rwanda with a large share of cold subhumid and cool-semi arid arable land will be the least affected.

Some of the limitations of this study include the fact that we used data from global climate models which do not adequately capture monsoonal processes and precipitation patterns in East Africa. Hence these uncertainties will equally be propagated into model input and outputs. We did not explore extreme or seasonal climatic variation, which should be helpful for better assessment of the agricultural potential and adaptation, especially in fragile agro-ecological zones. Our result could further be improved with finer or regional agricultural and agro-ecological zones dataset of the study region. Nonetheless, our results highlight the vulnerability of legumes crops as well as their production zones which could be the first step in the formulation of adaptation strategies for the study region.

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