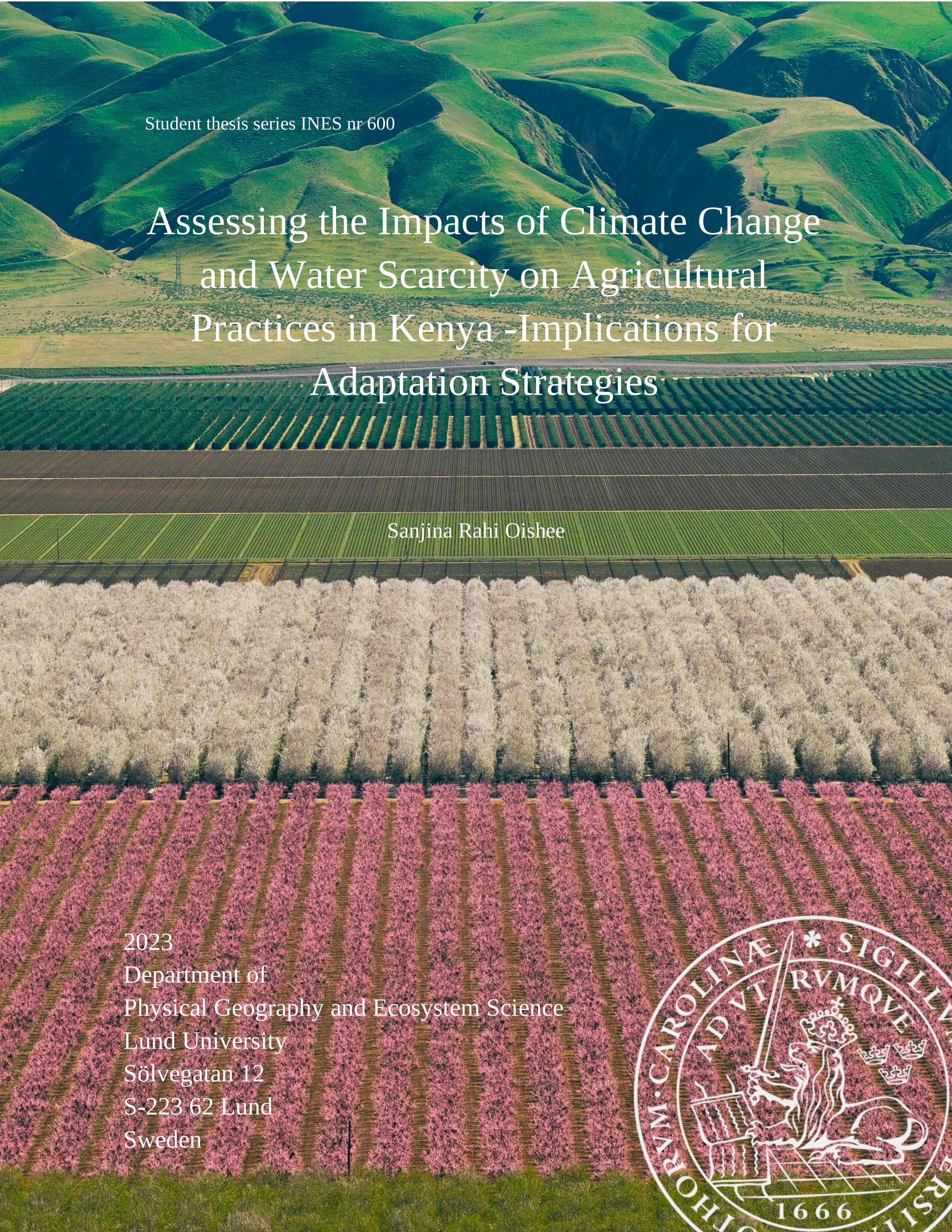

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Assessing the Impacts of Climate Change and Water Scarcity on Agricultural Practices in Kenya -Implications for Adaptation Strategies

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Bachelor thesis, 15 credits, in Physical Geography and Ecosystem Analysis

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Course
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Abstract

Like other African countries, Kenya’ economy and food security is heavily dependent on agriculture. Climate change has led to variability in temperature and precipitation, and extreme weather events such as droughts and floods, all of which can significantly impact crop productivity and food security in the long-term. Furthermore, water scarcity poses a critical challenge for Kenya, particularly in arid and semi-arid regions, where limited rainfall and increasing demand have led to diminishing water levels in rivers, lakes, and groundwater sources. This study assesses the impacts of climate change and water scarcity on agricultural practices in Kenya by modelling Agro-Climatic Zones (ACZ) based on climate and elevation and therefore predicting a shift in these zones based on future climate projections of the highest emission scenario (RCP 8.5). From the climate projections, it is predicted that mean annual temperature and precipitation will increase by 1.7°C and 34.7mm in the near future (2041-2050) and by 2.8°C and 120.2mm in the far future (2071-2080). The findings reveal that due to this change in climate, the ACZ’s of high to medium agricultural suitability are projected to decrease. Therefore, a country wide decrease of roughly 20% in production of some major crops are projected in the near-future while a further 10% can be anticipated in the far-future. The ACZ’s will further be affected by water scarcity as agriculture and water are linked. This study also links climate change to the major natural renewable water sources of Kenya which plays an important role in agriculture. Therefore, water scarcity is investigated by using natural renewable water sources and population as proxy. The results indicate that climate change is projected to affect these water sources mainly due to the precipitation change, however, coupled with a potential increase in population, this will exacerbate water stress in Kenya. And finally, through the study's findings, possible recommendations for policymakers for adaptation strategies are made, the main ones include more investments in the areas with high to medium crop suitability to maximize agricultural productivity and implementing laws and regulations for protecting Kenya’s main water sources.

Keywords: Climate Change, Agriculture, Temperature, Precipitation, Water Scarcity, Agro-Climatic Zone

Table of Contents

1. Introduction

Climate change and its associated impacts on agriculture are growing worldwide, especially in African nations (Kogo et al., 2021, 2022). Around 80% of the population in Africa rely on agriculture for their livelihoods (Poulton & Kanyinga, 2014), which is largely dependent on rain-fed farming (Kogo et al., 2021, 2022; Ochieng et al., 2016). Agriculture contributes up to 55% of the continent's gross domestic product. Despite playing such a significant role, the agriculture sector is nevertheless susceptible to the effects of climatic variability and change, which have been associated with the loss in agricultural production in sub-Saharan Africa over the past 50 years (Herrero et al., 2010.; Kogo et al., 2021).

Previous studies (Kalele et al., 2021; Kogo et al., 2021, 2022) have demonstrated the detrimental influence of climate change on agricultural productivity in sub-Saharan Africa. These effects exacerbate existing challenges like unfavorable topography, poor soils, limited incentives for intensification, inadequate market access, and subpar agricultural policies (Poulton & Kanyinga, 2014). Like other African countries, Kenya heavily relies on agriculture, which accounts for 65% of national exports and 70% of informal rural employment (Poulton & Kanyinga, 2014). However, population growth, encroachment on marginal lands, and urbanization trends are straining the country's natural resources, especially water (Odawa & Seo, 2019; Okello et al., 2015). As global urbanization continues to rise, with projections indicating that 70% of the world's population will live in cities by 2050 (Rockström & Barron, 2007), the demand for water, including for agriculture, is expected to increase.

Climate change has led to variability in temperature and precipitation, and extreme weather events such as droughts and floods, all of which can significantly impact crop productivity and food security (Kalele et al., 2021). Kenya's agriculture relies mainly on the bimodal rainfall pattern, and as a result, 85% of the population depends on rainfed farming (Kogo et al., 2022). Only 16% of Kenya's land is thought to get sufficient and consistent rainfall, making only a small portion of the country ideal for crop production (Kalele et al., 2021). Therefore, a potential change in rainfall patterns within this area due to climate change can heavily impact the agricultural sector of Kenya. Furthermore, water scarcity poses a critical challenge for Kenya, particularly in arid and semi-arid regions, where limited rainfall and increasing demand have led to diminishing water levels in rivers, lakes, and groundwater sources (Mulwa et al., 2021). Sustainable management and conservation measures are essential to safeguard Kenya's natural renewable water resources and ensure agriculture, food security, and ecosystem sustainability.

While studies on the impact of climate change on agriculture have been undertaken globally, few studies have focused on developing countries, especially country-specific studies that can provide detailed assessments and evidence of the past and future effects of climate change and its impacts on water scarcity which are a source of important decision making for local authorities and population. Therefore, this study seeks to fill this gap by assessing the impacts of climate change and water scarcity on agricultural practices in Kenya and drawing implications for adaptation strategies to enhance the sector's resilience to these consequences.

1.1 Aims and Objectives

The aim of this thesis is to assess the impacts of climate change and water scarcity on agricultural practices in Kenya. The study's findings will inform policymakers and stakeholders in the agricultural sector on the necessary measures to mitigate the negative impacts of these challenges and enhance sustainable agricultural practices in Kenya. The aims are divided into five main objectives:

1. To identify the current location of Kenya's existing croplands

2. To observe how Kenya's climatic classes are currently organized in terms of temperature and precipitation, and how will they evolve in the future for the two time periods, 2041-2050 and 2071-2080 based on Representative Concentration Pathway (RCP) scenario 8.5, which is a very high greenhouse gas emission scenario (Riahi et al., 2011). Additionally, to identify areas that will be the most vulnerable to climate change (areas that experience a high magnitude of change in temperature and/ or precipitation)

3. To model current Agro-Climatic Zones (zones that depict areas of least suitability to high suitability for agriculture) located in Kenya using current climatic classes (temperature and

precipitation), elevation data and location of current croplands. Additionally, analyze how will they change for the future climate projections using the projected climatic classes

4. To analyze how water scarcity can affect Kenya under ongoing climate change. In this study, water scarcity is mainly determined by the five “Water Towers” of Kenya (catchment areas located in the highland areas and are the main natural renewable water resources), population density and location of croplands

5. To provide recommendations for policymakers and stakeholders for adaptation strategies that can be employed to improve agricultural practices in Kenya and enhance the sector's resilience to the impacts of climate change and water scarcity

2. Methods, Materials, and Data

2.1 Study Area

This thesis explores the study area of Kenya, a country located in Eastern Africa, with a population of approximately 52.6 million people (2019) (*WBG*, 2021). Situated at approximately 1° South latitude and 38° East longitude, Kenya covers a total of 582,646 km^2 (*WBG*, 2021). It is bordered by Ethiopia in the north, South Sudan to the northwest, Somalia to the northeast, Tanzania to the south, Uganda to the west, and the Indian Ocean to the southeast (Figure 1). Kenya's diverse geography encompasses a wide range of ecosystems, from coastal plains to highland plateaus and the Great Rift Valley (*WBG*, 2021).

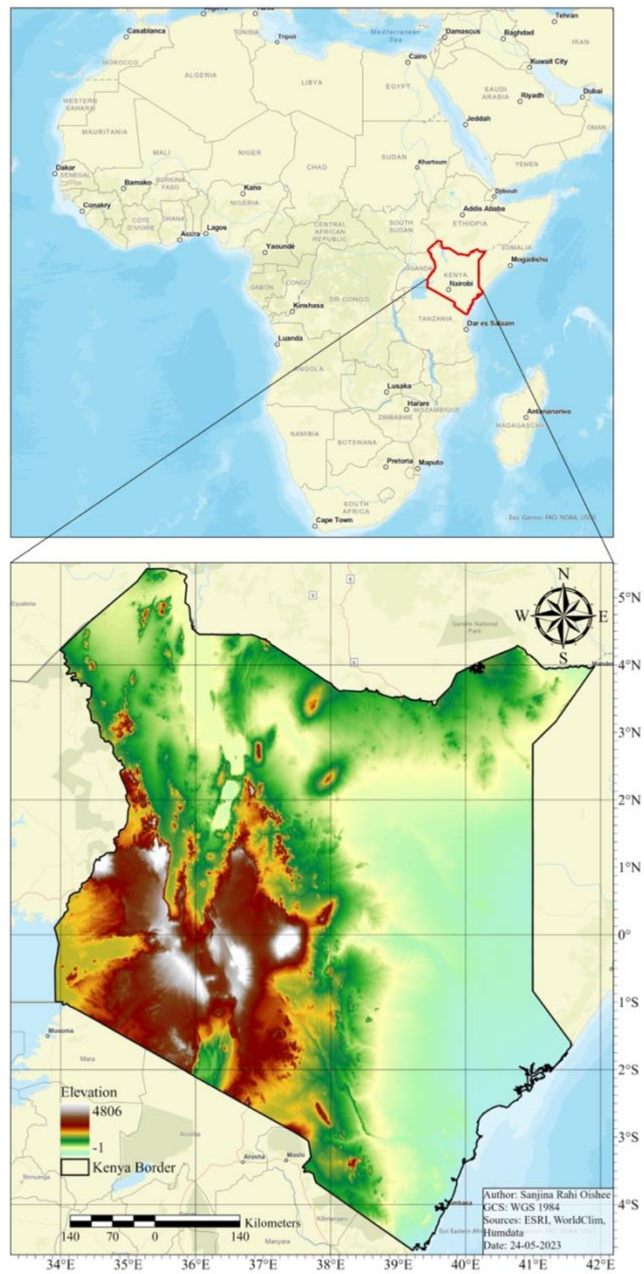

Figure 1: Elevation map of Kenya, Africa

The climate in Kenya varies across the country, but it is generally characterized as tropical, with distinct wet and dry seasons. This variation in climate is the result of the diverse topography across the country, proximity to the equator, the Indian Ocean and the Intertropical Convergence Zone (ITCZ). However, the primary climatic factor responsible for Kenya’s variation in rainfall is the ITCZ (Ng’ang’a, 1992). The average temperature in Kenya ranges from 18°C at the high elevation areas to 26°C along the coast, while the annual precipitation varies considerably from 250 mm in arid regions in the north to over 2,000 mm in some coastal areas and highlands in the west (*WBG*, 2021).

Roughly 80 percent of total water demand is met by surface water in Kenya. An estimated 75% of surface water originates from the five "water towers" located in central and western Kenya (Mulwa et al., 2021). These include Mt. Elgon, Cherangani Hills, Mau Forest Complex, Aberdare Ranges and Mt. Kenya. Water towers are referred to as the high elevation catchment areas in the country where the climate is humid. This water supply supports human consumption and agricultural practices. Therefore, looking at how these main catchment areas will be affected in the future due to climate change is very critical for the future of Kenya.

2.2 Data, sources and methodology

2.2.1 Land Use and Kenya data

Land Use data 2019 from Global Land Analysis and Discovery (GLAD) (Hansen et al., 2022), with a spatial resolution of 1 arc-second per pixel, was used to extract only the cropland within the region of Kenya, other land use classes were disregarded. After the croplands were extracted from this layer, the data was resampled to have a spatial resolution of 1 x 1 km and was then overlaid with the administrative borders of Kenya. Data for Kenya were extracted from Humanitarian Data Exchange (*Kenya - HDX*, n.d.) and then used to create a map highlighting the agricultural areas to look at the most recent agricultural practices (Objective #1).

2.2.2 Climate

Coordinated Regional Climate Downscaling Experiment (CORDEX) (*CORDEX | ESGF-CoG*, 2016) climate data, which includes precipitation and surface air temperature, are used from Earth System Grid Federation (ESGF), with a resolution of 50 x 50 km. The following search criteria were used as search engine input to locate the specific CORDEX data utilized in this study: pr/tas, AFR-44, NOAA-GFDL-GFDL-ESM2M, historical/rcp85, r1i1p1, SMHI-RCA4, v1, mon, 1981 – 2005/2041 – 2050/2071 – 2080. Further explanation of each variables is provided in table 1.

Table 1: Breakdown of criterions used in ESGF search engine (CORDEX | ESGF-CoG, 2016)

Variables	Description
pr/tas	Climatic variables: Precipitation/ Surface air temperature
AFR-44	CORDEX dataset for Africa
NOAA-GFDL-GFDL-ESM2M	Climate model developed by National Oceanic and Atmospheric Administration (NOAA) in collaboration with the Geophysical Fluid Dynamics Laboratory (GFDL). Model name: "GFDL Earth System Model version 2M"
historical/rcp85	Historical period/ Representative Concentration Pathway 8.5, which is a scenario used in climate modeling to represent a high greenhouse gas emissions future
r1i1p1	Ensemble member identifiers often used in climate modeling to represent different runs of the same model
SMHI-RCA4	Climate model or dataset, developed by the Swedish Meteorological and Hydrological Institute (SMHI). "RCA4" indicates the version or variant of the model
v1	Version number of dataset or model.
mon	Monthly dataset
1981-2005/2041-2050/2071-2080	Time periods specified for the analysis. 1981-2005 is the historical period, while 2041-2050 and 2071-2080, represent future periods under the specified scenario (rcp85)

The most recent historical data found was from 2001-2005. The datasets were extracted and managed using Climate data operators (CDO) (*Climate Data Operators (CDO)*, 2012.) and Geospatial Data Abstraction Library (GDAL Python) (Rouault, Even et al., 2023) . The CORDEX climate dataset consists of multi-year monthly time series. The "ymonmean" function on CDO was used to calculate the monthly average of the multi-year time series datasets. GDAL is then used to convert the NETCDF files to tiff files to allow use in ArcGIS Pro 2.8 (Esri, 380 New York

Street, Redlands, CA 92373-8100 USA) for data analysis. In order to establish a stable climate baseline for the historical climate, an average of the historical climate data from 1981-2005 is used. Projected climate data were taken from the climate scenario RCP 8.5 to analyse a high-emission scenario of greenhouse gasses. RCP 8.5 scenario was selected in order to provide a realistic depiction of a future where emissions are largely uncontrolled and therefore provides insight on the worst-case scenario. Two time periods, a near-future, one from 2041-2050, and a far-future one, from 2071-2080, were investigated.

After extraction, climate data were analyzed in ArcGIS Pro. An annual mean is calculated for the historical and projected climate data by calculating the mean of all the 12 months. A historical climate baseline from 1981-2005 along with two different future climate scenarios were produced: projected climates from 2041-2050 and 2071-2081. The historical climate data were classified into 5 categories and were divided using natural breaks on ArcGIS Pro (table.1). A natural break is a statistical method used to determine meaningful groupings or intervals in a dataset. The process involves iteratively comparing the variances between adjacent groups, seeking points where the variances are significantly different. These points indicate natural breaks or transitions in the data, allowing for more meaningful and interpretable grouping (Chen et al., 2013) . These ranges were then applied to the projected climate data to form climate classes for 2041-2050 and 2071-2080. Natural breaks were used to classify mainly because they were more representative for the study area and allowed better identification of temperature and precipitation patterns within the country. This produced five distinct classes for temperature and precipitation, both categories ranging from "Very Low" to "Very High" shown in table 2. Where "Very High" indicates zones with the highest temperature range within the five classes and vice versa.

Table 1, shows how Kenya's climate classes (T and P classes) are organized, where climate class "Very Low" indicates either "Very Low" temperature class or "Very Low" precipitation and vice versa. Future projections from P and T are then categorized using this table to observe how the climate classes shift in the future for the two time periods, 2041-2050 and 2071-2080 based on RCP scenario 8.5 (Objectives #2).

Table 2: Kenya's r Temperature (T) and Precipitation(P) classes (Climate class) where T is mean annual degree Celsius (°C) and P is mean annual millimeters of rainfall (mm).

Mean Annual Temperature (T) (°C)	**Mean Annual Precipitation (P) (mm)**	**Climate Class**
12.8-17	<517.8	Very Low
17-20.5	517.8-1076.4	Low
20.5-23.5	1076.4-1980.7	Medium
23.5-25	1980.7-3550	High
25-30	>3550	Very High

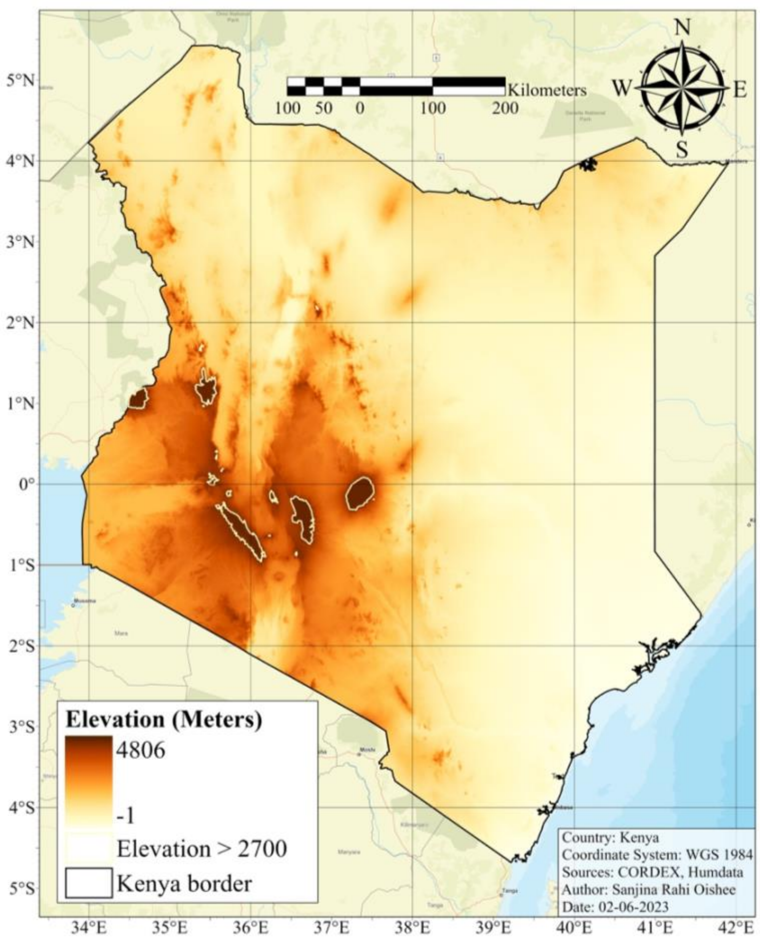

Figure 2: Kenya elevation map highlighting areas that are greater than 2700 meters in height

2.2.3 Elevation

Elevation data from WorldClim (Fick & Hijmans, 2017), with a spatial resolution of 1*1 km, was used to exclude areas with elevation > 2700 meters. When elevation data was overlayed with the cropland layer, it was observed that areas of high elevation were not used for agriculture and the maximum elevation where croplands were located was around 2700 meters. Since these areas had no croplands, even though the climatic conditions may allow suitable agricultural conditions, they were categorized as areas with overall very low suitability for agriculture.

Elevation in Kenya varies from 4806 to -1 meters. The outlined areas in figure 2 represent areas that are excluded from area of suitability for cultivation or agriculture.

2.2.4 Water scarcity

To investigate water scarcity in a more general aspect, natural water resources and population density were assessed and used as proxy. Natural renewable water resource data were extracted from existing maps from other literature studies (Mulwa et al., 2021). The map identifies the five main catchment areas or "water towers" of Kenya. The map was then georeferenced and the areas were manually digitized for further spatial analysis in ArcGIS Pro. A gridded population density data was obtained from Center for International Earth Science Information Network (CIESIN, 2018) with a resolution of 2.5 arc-minutes. Population density for the year 2000 is used and is in the unit persons per square kilometer.

2.3 Data Analysis

Data analysis is mostly done in ArcGIS Pro while the statistical analysis is done in MS Excel. Surface temperature and precipitation classes (Table 1) are used to create "Climatic zones" by overlapping the temperature and precipitation ranges for each zone according to the T and P classes. In order to categorize the "Climatic zones" according to agricultural suitability, the cropland locations were used. The cropland data, when overlaid with the "Climatic zones", a clear pattern was observed between them. The main trends identified were, high cropland density in "Climate zones" that have both "Very high" P and "Very Low" T while very low to no croplands located in "Climate zones" that have "Very Low" P and "Very High" to "High" T. Elevation data are also included, where areas greater than 2700 meters in elevation (E) are catagorised as not suitable for agriculture (table 2).

As a result, the four-following distinct ACZ's were created (table 3) according to agricultural suitability, temperature, precipitation and elevation. The model input variables and conditions for the following ACZ's are as follows:

a) Zone I, Very Low suitability/ no suitability
    i. "Very High" to "High" T **OR**

ii. “Very Low” P **AND**

iii. E > 2700 meters above sea level

b) Zone II, Low suitability

i. “Very High” to “Low” T **OR**

ii. “Medium” to “Very Low” P **AND**

iii. E < 2700

c) Zone III, Medium suitability

i. “Medium” to “Very Low” T **OR**

ii. “Medium” to “Low” P **AND**

iii. E < 2700

d) Zone IV, High suitability

i. “Low” to “Very Low” T **OR**

ii. “Very High” to “Medium” P **AND**

iii. E < 2700

Table 3: Agro-climatic zones with their corresponding agricultural suitability, climatic conditions (T &P) and elevation criteria

ACZ	Agricultural Suitability	Mean Annual T (°C)	Mean Annual P (mm)	Elevation (m)
I	Very low/no suitability	23.5-30	39-517.8	>2700
II	Low suitability	17-30	39-1980.7	<2700
III	Medium suitability	12.8-23.5	517.8-1980.7	
IV	High Suitability	12.8-20.5	>1076.4	

These were then used to create a map for the current ACZ in Kenya. These input variable and conditions are further applied to the future projected “Climate classes” to identify the new ACZ’s. These are further mapped and analysed to see how climate change can potentially cause a shift of the ACZ’s in the future (Objectives #3).

In order to look more into how the climate differs from the present (1981-2005) to the future projections (2041-2050, 2071-2080), the T and P change were calculated by subtracting the present climate layers from the future climate layers. These results are used to create T and P change maps with overlaying the major cities of Kenya (figure 6 & 7). This analysis in mainly aimed to pinpoint areas that will be most vulnerable to climate change in the near- and far future (Objectives #2).

To evaluate water scarcity in Kenya, the five main "water towers" of Kenya were used and overlaid with other variables such as population, T and P change in order to assess whether or not they will have an impact in the future (figure 10, 11 & 12). Additionally, the T and P change within the water towers ecosystems were assessed to evaluate its vulnerability to climate change (Objectives #4).

Lastly, with the help of this analysis and additional literature reviews, this study recommends adaptation strategies that can be employed to improve agricultural practices in Kenya and water scarcity and therefore enhance the sector's resilience to the impacts of climate (Objectives #5).

3. Results

3.1 Cropland Distribution Today

Figure 1 shows how the croplands are distributed within Kenya for the year 2019. This distribution of croplands demonstrates how and where agricultural practices are most suitable and least suitable according to not just climate but also the geographic location of the country's inhabitants. Most of

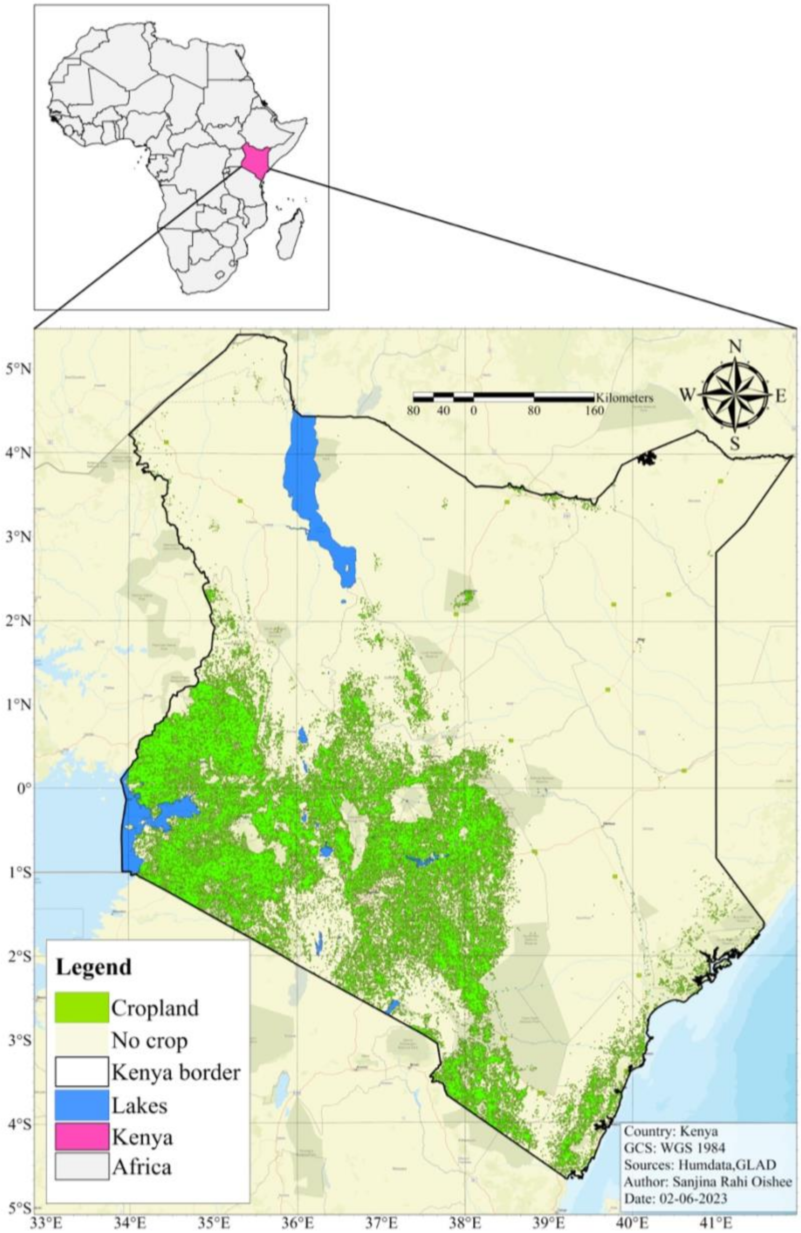

Figure 3: Cropland distribution of Kenya, Africa

the croplands are situated in the central, western and coastal part of the country. These areas are also locations which house nearly 90% of Kenya's population (*WBG*, 2021). It can also be noted that most of the croplands lie within or close proximity to the major cities of Kenya including Nairobi, Mombasa, Nakuru and Kisumi and cover almost 15 % of Kenya. A relationship between population and agricultural demand is clear as areas of higher population density would need to meet higher food demands.

3.2 Climate Today

Figure 4 shows how the observed average annual temperature and precipitation, from 1981-2005, vary spatially across Kenya. The mean annual temperature for Kenya is 24.1°C where the maximum average temperature is 28.3°C, observed mainly in the north and close to the coast, while the minimum average being 12.9, observed mainly in the central areas of the country with high elevation.

Inter Tropical Convergence Zone, which is located near the equator, heavily influences Kenya's climate, especially precipitation (*WBG*, 2021). Precipitation shows a distinct pattern as temperature, where areas of very high elevation experience the highest rainfall annually, which is over 6000mm per year. However, areas in the north along with areas of low elevation experience the lowest rainfall annually which is around 40 mm per year, while the mean annual precipitation of Kenya during this time period is 587.5 mm.

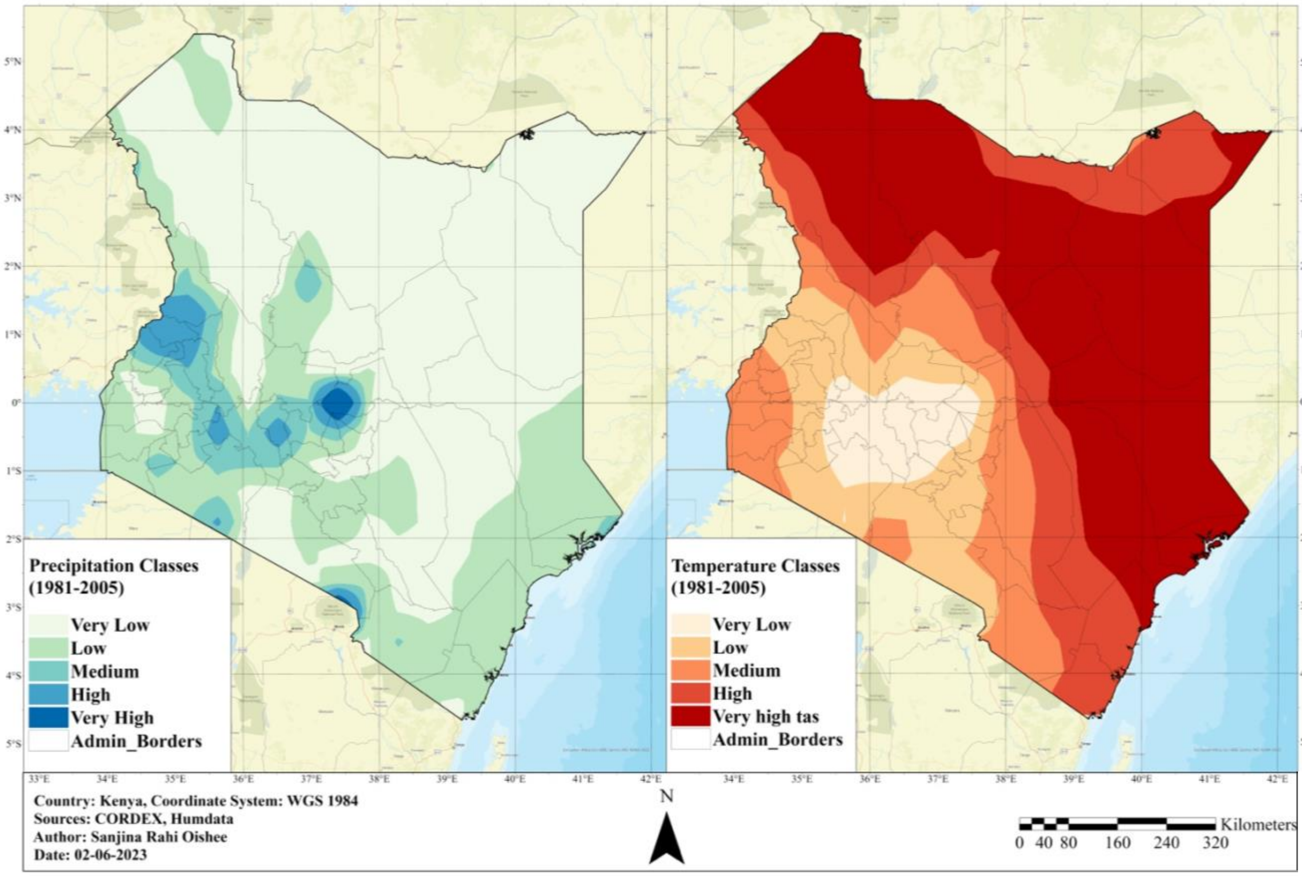

Figure 4: Historical climate from 1981-2005 showing different precipitation and temperature classes within Kenya

3.3 Agro-Climatic Zones (ACZ)

Current ACZ's are modelled according to historical (1981-2005) temperature and climate, elevation. This is illustrated in table 4, along with the percentage of Kenya each covers, percentage of zone consisting of croplands and percentage of croplands hosted within each zone. Agricultural suitability of each zone also differs from "Very Low/No Suitability" to "High Suitability". It should be noted that even though areas of elevation greater than 2700 meters meet the ACZ IV, requirements, they are categorized as ACZ I (Very Low/No Suitability). This is due to the fact that no croplands are currently located in these elevations and are assumed to be not used for croplands in the future. This is mainly because the five main “Water Towers” of Kenya are located in these regions, therefore restricting agricultural practices.

Table 4: Modelled ACZ’s with their respective agricultural suitability, % of Kenya it occupies, mean annual T (°C) and P (mm) conditions, % of ACZ covered with croplands and lastly % of croplands hosted in each ACZ

ACZ	Agricultural Suitability	% of Kenya occupied	Mean Annual T (°C)	Mean Annual P (mm)	% Zone covered with croplands	% Cropland hosted
I	Very low/no suitability	52	23.5-30	40-520	~ 1.5	~5
II	Low suitability	23	17-30	40-1980	15	23
III	Medium suitability	18	12.8-23.5	520-1980	30	46
IV	High Suitability	7	12.8-20.5	>1080	55	26

Figure 5 shows how the four ACZ’s are located within Kenya. It can be observed that majority of the non-suitable agricultural areas are located in the arid part of the country including areas of high elevation due to restrictions (location of water towers). Majority of the suitable agricultural areas are located in the western while some the central and southern part of the country. It should also be noted that areas of high elevations are quite suitable for agriculture due to optimal climatic conditions (relatively high precipitation and low temperature).

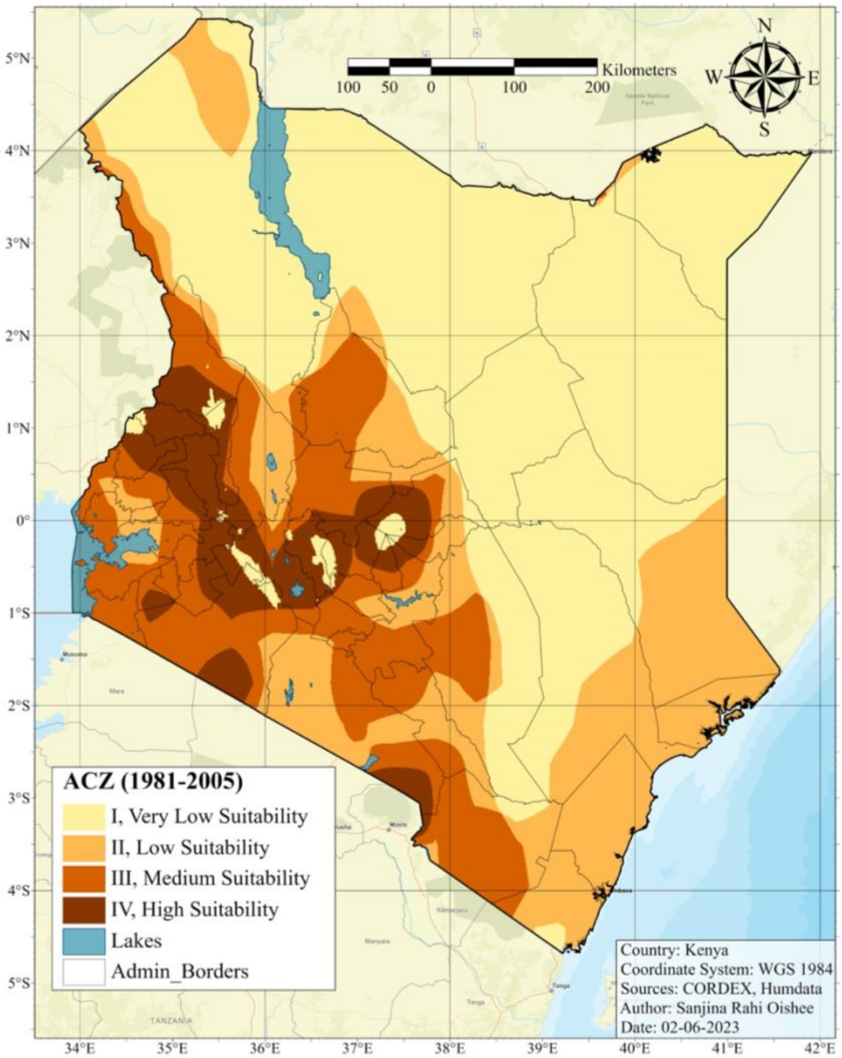

Figure 5: Agro-Climatic zones based on historical climate

3.3.1 ACZ I: Very Low/No Suitability

This zone has no agricultural importance in Kenya, therefore is categorized as area of "Very low/ no suitability" (figure 5). This zone includes mountainous regions (elevation > 2700 meters) and areas that experience very high to high temperature, ranging from 23.5-30 °C, along with very low precipitation less than 520 millimeters annually (arid conditions). Only around 1.5% of the zone is covered by croplands and hosts roughly 5% of the total croplands. This indicates that the area is in general not at all optimal for agriculture due to the fact that the climatic conditions are unsuitable to support a standard agricultural productivity and the population density is quite low, ranging from 0-90 persons per km^2.

3.3.2 ACZ II: Low Suitability

Only around 10% of the zone is covered by croplands, hosting about 23% of Kenya's total croplands. This zone is overall much wetter (40-1980mm) in contrast to Zone I (40-520mm) and some areas occur at parts that are in close proximity to the high elevation areas (>2700m), hence there is an increase in mean annual precipitation as areas of high elevation generally receive more rainfall comparatively according to figure 4. Therefore, there is an overall increase in mean precipitation paired with a much lower mean temperature range (17-30°C) compared to ACZ II.

3.3.3 ACZ III: Medium Suitability

This zone occupies areas of relatively high elevation (closer proximity to areas that have elevation >2700) compared to Zone II with some exceptions (along the coastline). However, it has a lower temperature range of 12.8-23.5 °C and an overall higher precipitation comparatively, with the exception of some areas receiving a relatively low precipitation of around 520mm. Therefore, due to a more suitable condition for agriculture, this zone hosts around 46% of the total croplands while 30% of the zone is occupied by croplands. Due to the fact that this zone consists of areas that receive low rainfall, it is assumed that some of the croplands would require irrigation. Even though this zone hosts around half of the total croplands, it should be noted that it covers almost 18% of Kenya. The population density is also much higher compared to zones I and II, therefore the demand for crops would also be greater.

3.3.4 ACZ IV: High Suitability

This zone is generally restricted to mainly highlands of Kenya (not more than 2700m in elevation) with areas that experience low to very low temperatures (12.8-20.5 °C) and with precipitation that ranges from medium to very high (greater than 1076 mm). This zone has the most agricultural significance as the climatic conditions and location is the most optimal for agriculture as the majority of the total zone (60%) is covered in croplands while hosting 26% of the total croplands. It should be noted that this zone occupies only around 7% of Kenya while 60% of it is covered in croplands, therefore making it the most agriculturally productive zone compared to others. Even though this region has the potential to host more croplands, this zone consists of the highest population density, therefore making a big part of the zone mostly cities and built-up areas.

3.4 Projected Temperature Change

In figure 6, it can be observed that there is an overall increase in temperature all over the country where the highest temperature increase is experienced majorly in the western, north-western and central part. The mean annual temperature for 2041-2050 is expected to be 25.8 °C while for 2071-2080 the mean is much higher with a value of 26.9 °C. When compared to the temperature change between historical and 2071-2080, the overall temperature change is much higher compared to the 2041-2050, hence the darker color gradient for the temperature in figure 6.

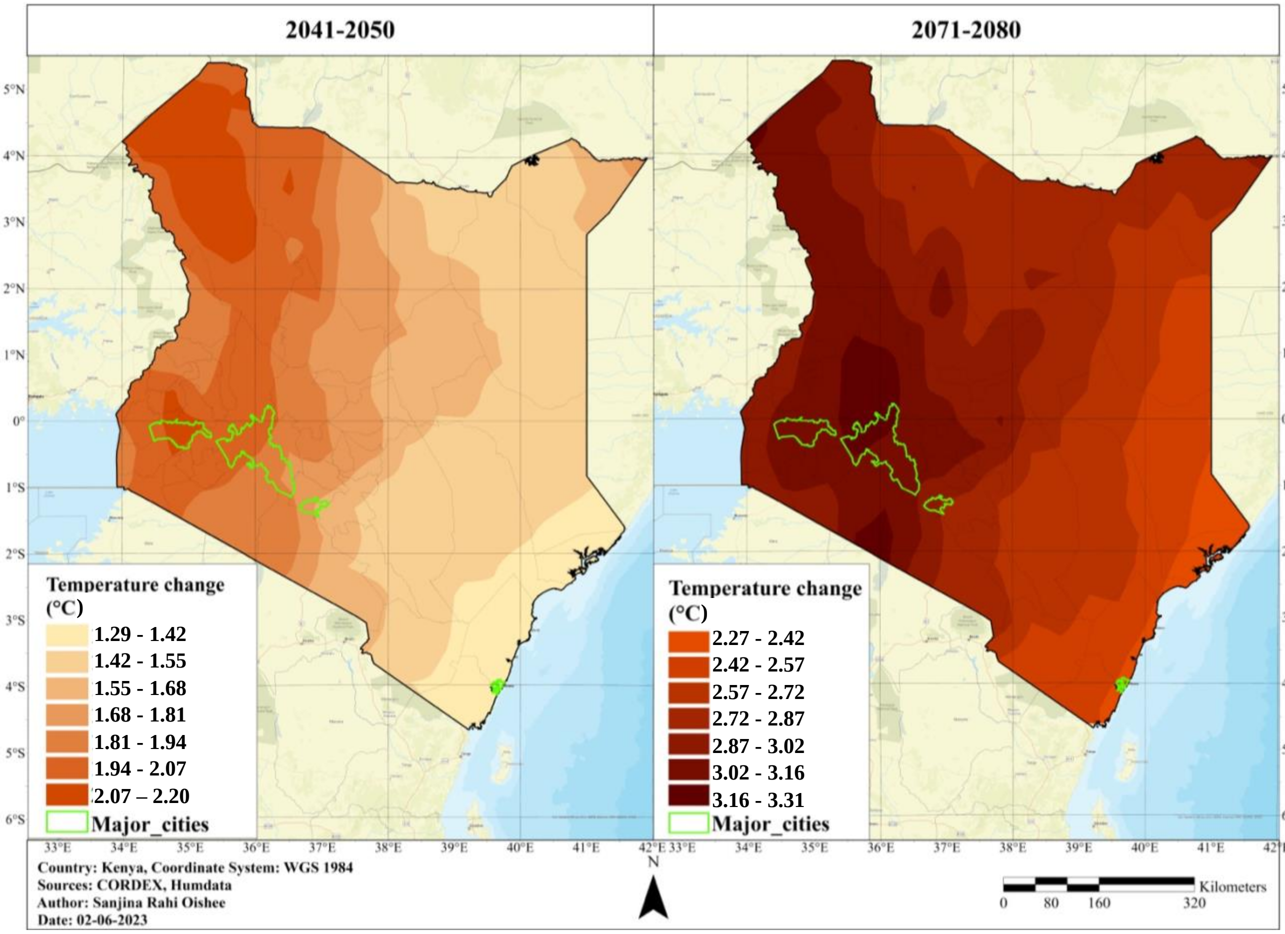

Figure 6: Projected temperature change in mean annual temperature by 2041-2050 and 2071-2080 relative to 1981-2005 baseline under RCP 8.5 which is the highest emission scenario.

A similar pattern in temperature change is followed for both the time periods; however, the western and area close to the center experiences the highest temperature increase for 2071-2080 (over 3°C where 3.31 °C is the maximum temperature increase). While the western and north-western regions experience the largest temperature increase for 2041-2050 (ranging from 1.94 – 2.2 °C). For both the changes, areas that were relatively cool in the historical period ("Low" to "Very Low" temperature classes in fig 3) have a much higher temperature change (increase) compared to the other temperature classes from fig3. Additionally, areas close to the coast, in the south-eastern part, experience a lower temperature change compared to the baseline (+1.29 – +1.42 for 2041-50; +2.27 – 2.42 for 2071-80). Major cities mainly, Nairobi, Kisumu and Nakuru, which are located in the western and central part of Kenya are projected to experience a higher change in temperature compared to Mombasa which is located near the coast of Kenya. This trend is apparent for both climate scenarios but the temperature change is much pronounced for the far-future scenario.

3.5 Projected Precipitation Change

In figure 7, precipitation change follows a distinct pattern for 2041-50, where areas of high elevation experience a prominent drying due to an overall decrease in mean annual rainfall (a precipitation decrease ranging from around 300 to a maximum of approximately 610 mm). Not much of an increase in precipitation is observed in the 2041-50 projection, just a slight is experienced in the eastern part of roughly 125-210 mm. In contrast to 2041-50, the precipitation changes for 2071-80 does not follow any distinct pattern, however, areas of high elevation do experience drying but not at a very high magnitude comparatively (a maximum of 476-356 mm decrease of annual precipitation).

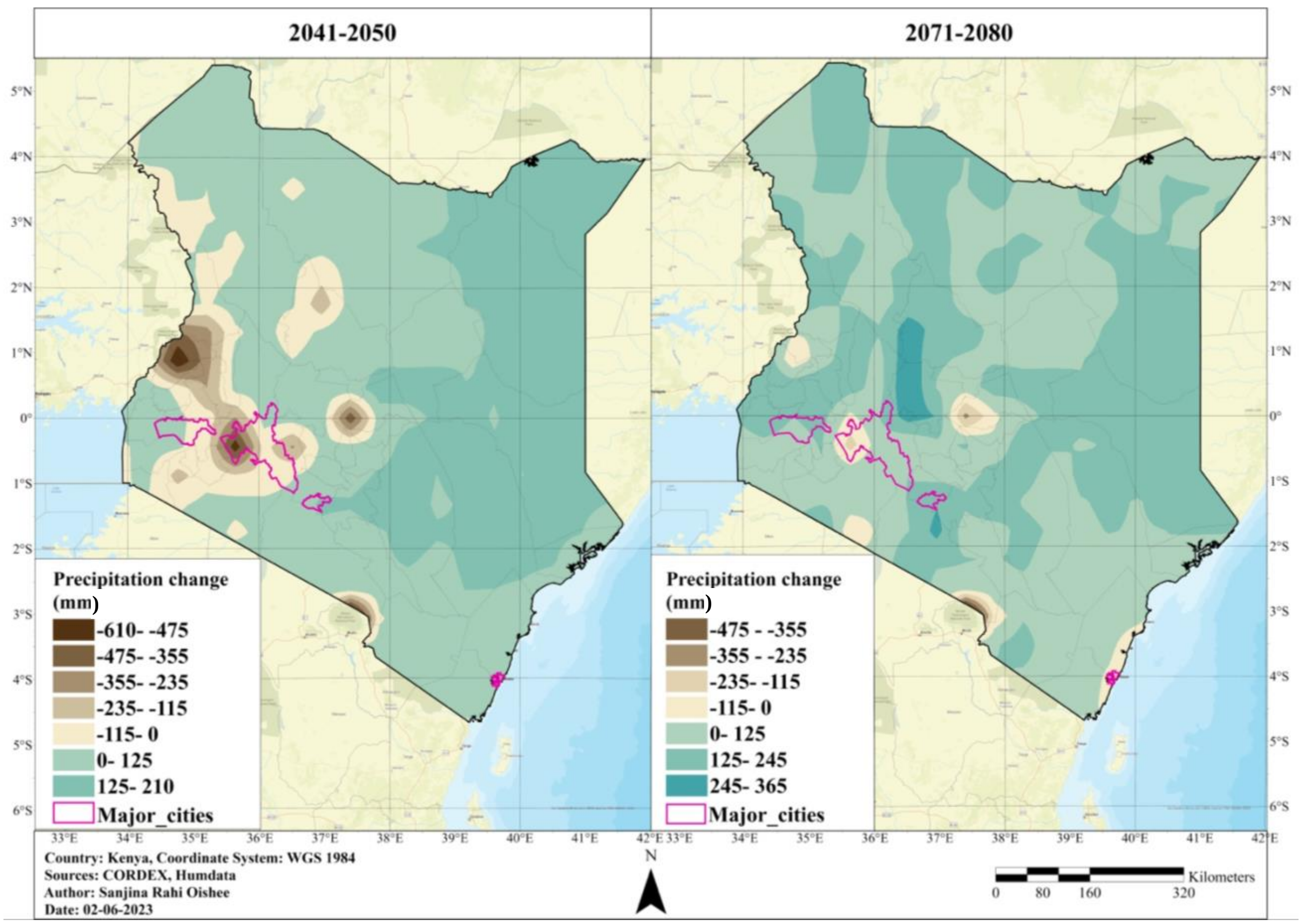

Figure 7:Projected precipitation change in mean annual precipitation by 2041-2050 and 2071-2080 relative to 1981-2005 baseline under RCP 8.5 which is the highest emission scenario.

Additionally, there are more areas that are experiencing an increase in mean annual precipitation (+125 – +365 mm), however not showing any trends other than a precipitation increase in areas of close proximity to the highlands along with regions in the north and east part of the country. It can therefore be observed that the spatial variability of precipitation within the country increases quite a bit in the climate projections. It should also be noted that the three of the major cities is expected to experience an overall drying due to a decrease in mean annual precipitation, these cities include Nakuru, Kisumu and Mombasa. Although, Nairobi is expected to have an overall slight annual increase in 2041-2050 and a furthermore greater increase in 2071-2080.

Table 5 exemplifies how the projected climate scenarios differ with mean annual T and P from the baseline period. The projected Climate scenarios have an overall increase in the temperature which is shown with the temperature ranges that have a much higher magnitude compared to the baseline along with a higher average of the mean annual temperature. Additionally, precipitation also shows a similar pattern where overall precipitation range is much higher in magnitude along with a higher mean annual. The far future scenario, however, has a much higher magnitude increase in both T and P compared to the near future scenario.

Table 5: Mean annual T & P range (from maximun to minimum) and mean of the mean annual T and P for the baseline and projected climate scenarios

Time period	Mean annual Temperature range (°C)	Mean annual precipitation range (mm)	Mean Annual Temperature (°C)	Mean annual Precipitation (mm)
1981-2005 (baseline)	28.3-12.9	6820-40	24.1	588
2041-2050	30.3-14.7	6350-50	25.8	622
2071-2080	31.2-15.9	6550-70	26.9	708

3.6 Shift in ACZ's- Present to future

A change in climate results in a shift of the ACZ's (figure 8), this is mainly due to the spatial and temporal variation of T and P in Kenya. This implies that some areas become more suitable for agriculture while others become less suitable. This model therefore predicts how ACZ's in Kenya shift due to the projected climate change and are therefore visualized in figure 8.

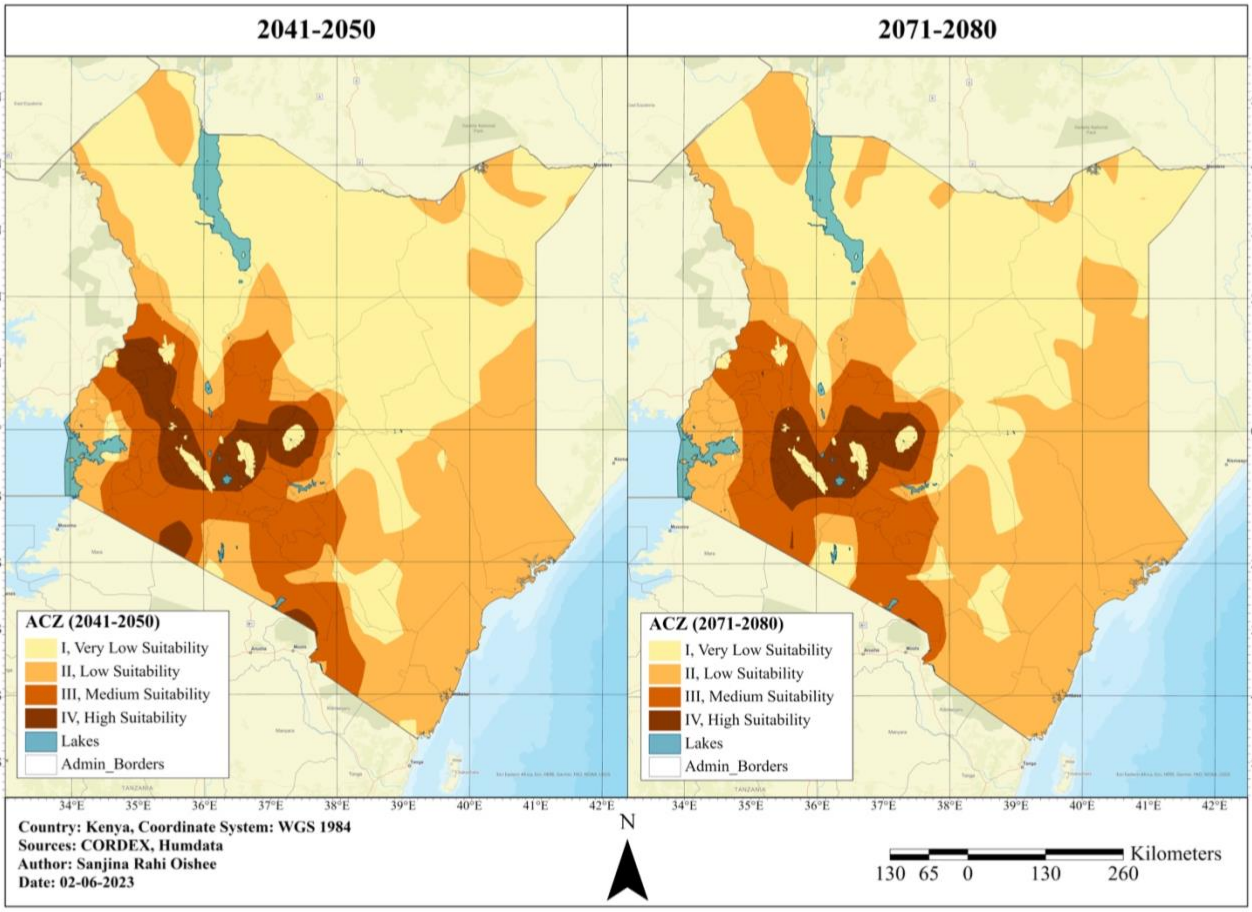

Figure 8: ACZ's based on 2041-2050 climate and 2071-2080 climate

Figure 9 illustrates how the ACZ areas are projected to change compared to the baseline period (1981-2005). The baseline period area for all the ACZ's are considered to be 100% in order to visualize the change better. Therefore, area lower than 100% indicates a decrease while and area greater than that indicates an increase. It can be observed that the area of ACZ I, III and IV are projected to decreases for both the future scenario while the area of ACZ II is projected to increase for both scenarios.

According to the model, the near future is projected to drop in agricultural productivity due to a loss of around 25% (figure 9) of ACZ IV which is highly suitable for agriculture. Similarly, ACZ III which has medium suitability will also decrease in area by nearly 15 %. Overall, areas which have "High" to "Medium" suitability are projected to drop by roughly 20% in the near future.

The far future scenario on the other hand, follows a similar, however the magnitude of change is much greater. ACZ IV is expected to drop almost 40% in area while the ACZ III is around 25%. Therefore, an overall higher decrease in areas (roughly 30%) which have “High” to “Medium” suitability are probable.

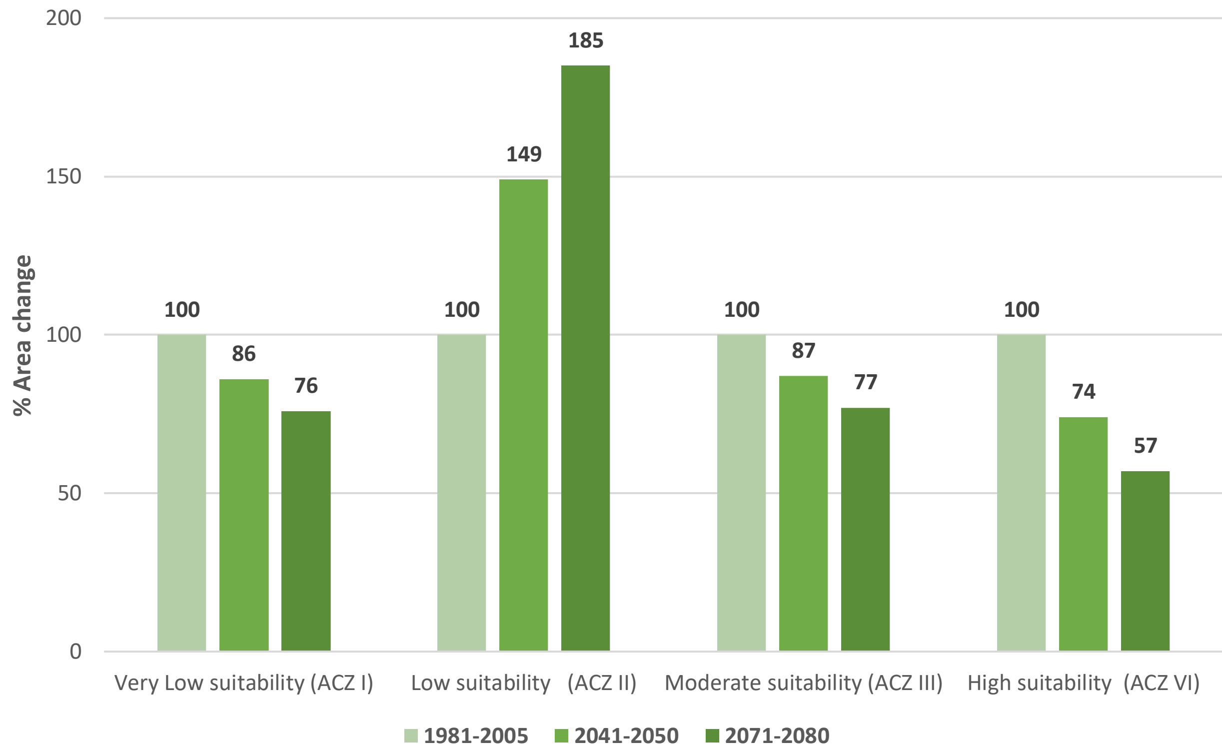

Figure 9:Area change for projected ACZ’s for near future (2041-2050) and far future (2071-2080) compared to baseline period (1981-2005)

ACZ II on the other hand, seems to be expanding into areas that were once ACZ I, III and IV for both future scenarios. Areas that were “high” to “medium” suitability for agriculture are projected to become less suitable while areas of “very low to no suitability” are becoming slightly more suitable for agriculture. This is due to the T and P change within the country resulting in a shift of the ACZ. There is a much more pronounced change observed for the far future, where there’s an over 80% increase in areas with “Low suitability” whereas the near future experiences an increase of about 45%.

Areas that are either of high or medium suitability are becoming less suitable for agriculture due to the shift in temperature and precipitation according to the model. On the contrary, areas that have almost no or very low suitability for agriculture are decreasing with time, this can be observed due to some areas experiencing an increase in precipitation therefore meeting the criteria for “low suitability” rather than “very low/ no suitability”.

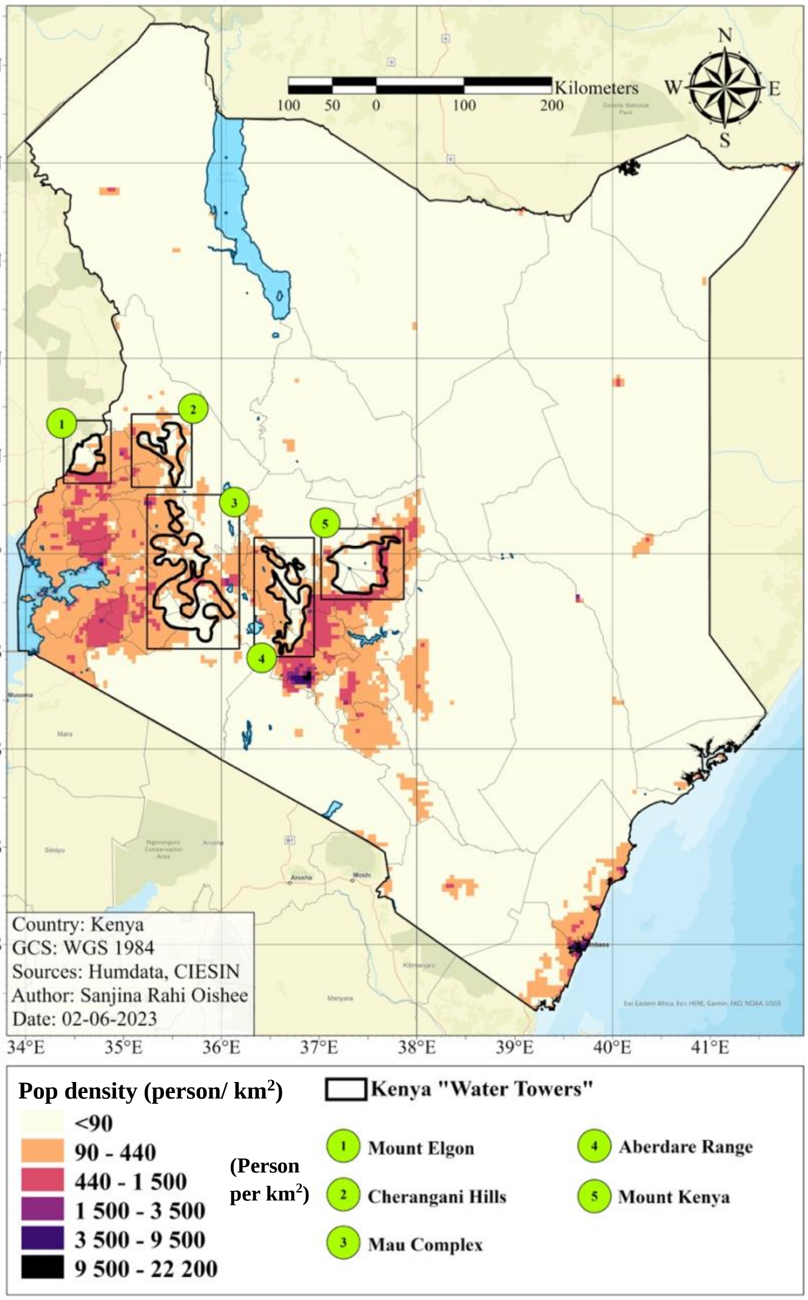

Figure 10: Five main "Water Towers" of Kenya with overlapping population density

3.7 Water Scarcity

Fig 9 shows the location of the five main “water towers” of Kenya paired with population density. These water towers are located within the proximity of areas of high population and major cities lie close by, with the exception of Mombasa which lies more towards the far south (close to the coast) of the country. The population is not homogenous, areas of high population density are mostly in the central and western part of the country, where the highest population density is observed in the country capital, Nairobi with more than 9500 people per kilometer square.

Figure 11 and 12 show how the temperature and precipitation will change within areas of the main water towers of Kenya. It can be observed that the catchment areas mainly lie in regions where there is a prominent change in temperature compared to the other parts of the region (mainly the eastern part). Mount Kenya and Mount Elgon are expected to experience a lower change in temperature comparatively. In terms of precipitation, there is a large precipitation change, drying specifically, within the catchment areas for the time period 2041-2050. However, the time period 2071-2080 shows a change of lower magnitude comparatively. There is also a variation of change, not just drying like in 2041-2050. Mount Kenya and Mau complex do experience an overall lower annual precipitation but the magnitude is much lower in contrast to 2041-2050. The other catchment areas experience a slight increase in annual precipitation. There is an overall lower amount of precipitation reaching the catchment areas annually.

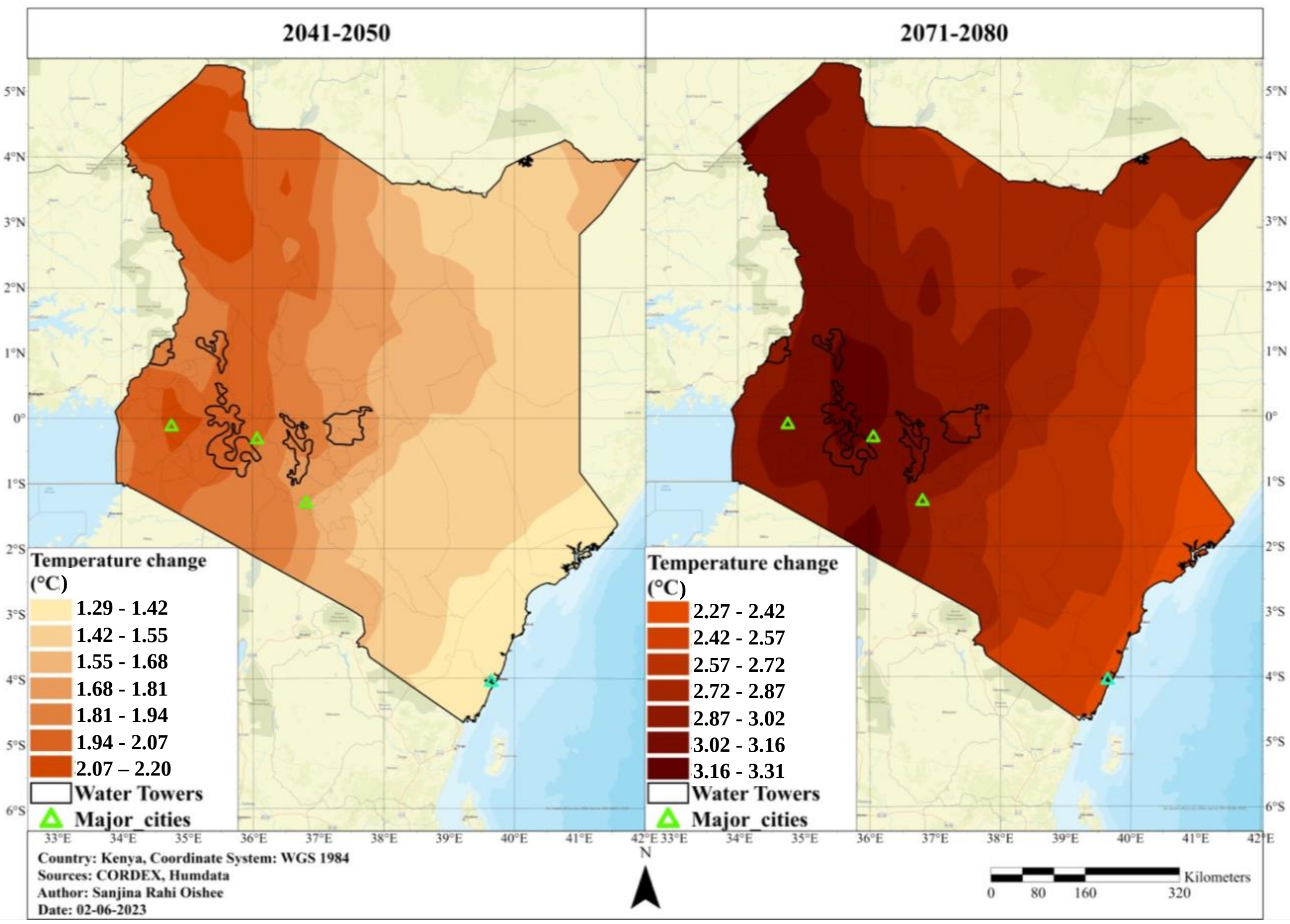

Figure 11: T change (°C) within the 5 main "Water towers" of Kenya

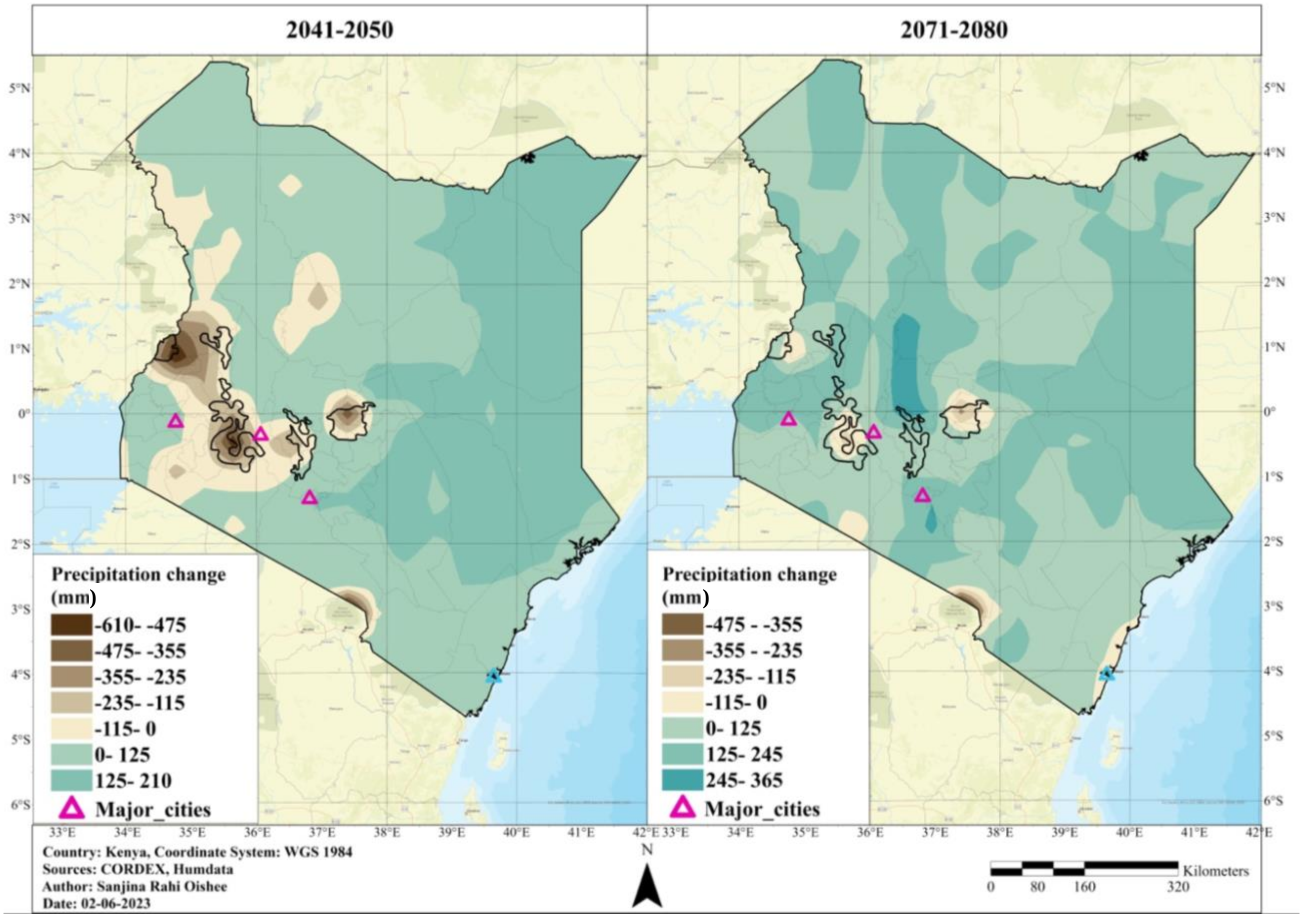

Figure 12: P change (mm) within the 5 main "Water towers" of Kenya

The mean annual temperature change that is projected to occur for 2041-2050 and 2071-2080 within these catchment areas are +1.88 °C and +3.09 °C respectively. Additionally, the mean annual precipitation changes that is expected to occure within the towers is -210 mm for the near future and +30 mm. Therefore, an overall increase is expected to be experienced within the catchment areas while the increase is much more pronounced in the far future scenario. However, the precipitation is projected to decrease quite a lot within the water towers for the near future, while the far future is expected to experience a slight increase.

4. Discussion

4.1 Climate change and ACZ shift

Future temperature predictions of the near future (2041- 2050) show that areas in the western parts experience a greater magnitude in T increase than the rest of the country. While the coastal areas, located in the east, also experience an increase T, this is at a much lower magnitude. The trend in

T distribution found in this study is also shown in research by *UCAR* (n.d.) and is mainly due to Kenya's proximity to the ocean. Simultaneously, precipitation follows a trend where there is an overall projected decrease in P in the western and central parts of Kenya, where the areas of high elevation experience the highest magnitude in precipitation decrease. This is the same area where a large portion of croplands and the most suitable ACZ's are located.

Areas classified as suitable for agriculture, according to the modelled ACZ's, are heavily affected by the projected T and P change. This is due to a decreased area of ACZ- IV (Agro-Climatic zone with the highest agricultural suitability) caused by the decrease in precipitation paired with an increase in temperature, affecting the zone's suitability. Rainfall influences the soil moisture and in combination with temperature affects the length of the crop's growing season and how much water the crops require to thrive (Kogo et al., 2021). Therefore, a combination of the two variables P and T, with respect to climate change, can influence agriculture and the ACZ's in this study. Furthermore, the precipitation change seems to be the main driver of this change in area of Zone VI, as precipitation within this zone experiences a higher variability compared to temperature. Previous studies have also shown to agree that precipitation is vital for the growth of crops compared to temperature (Shuai et al., 2018; Kogo et al., 2021, 2022).

The far future scenario (2071- 2080), displays a similar trend in temperature change as near-future, however, the magnitude of the change is far greater comparatively. The minimum temperature change observed for the far-future (+2.27 C) is higher than the maximum T change observed for the near future (+2.20 C). This indicates a far greater temperature rise in the future. This rapid increase from near- to far future is mainly due to the high emission scenario of RCP 8.5 used in this study (WBG, 2021). Precipitation change depicts no distinct pattern throughout the country, other than some highland areas receiving less mean annual precipitation. Studies have shown that precipitation is projected to remain highly variable and uncertain, however the average annual rainfall is expected to increase (WBG, 2021). This study's projection follows similar patterns as well. This change in both precipitation and temperature results in a further decrease in the areas of suitable agricultural conditions according to the model.

Despite the findings showing an increase in the mean precipitation from historical to 2041-2050 to 2071-2080, the seasonal spacing and timing of the precipitation are not taken into consideration and can vary a lot, creating a more extreme climate (Ochieng et al., 2016). Extremities of dryer and wetter areas are equalized in the annual mean and not shown in the scope of this study. The time period 2071 – 2080 consequently shows a decrease in the overall area of the most suitable zone for agriculture. The variability in precipitation combined with an increase in evapotranspiration, due to an increase in temperature, can be a reason why this happens. Therefore, a country wide decrease in production of some major crops such as maize, sorghum, millet, groundnut and casava, are to be expected. Bryan et al. (2013) predict that by 2050, the overall yield can be reduced by 8 to 22 percent unless key improvements are made in the agricultural sector of Kenya. Similarly, this study predicts a country wide decrease of roughly 20% in production of some major crops in the near-future while a further 10% can be anticipated in the far-future.

Additionally, some areas that were previously categorized as “Not Suitable” due to arid conditions are projected to change into areas that have “Low Suitability” for agriculture due to a relatively large increase in P and only a small change in T. This ACZ may have slightly more suitable conditions according to the model, and therefore able to better support agriculture, given that irrigation and maintenance are done. Even if suitability is increased, it is still categorized as “Low” since the agricultural productivity will not be sustainable due to the number of resources that are needed to harvest a suitable number of crops. Additionally, even with an increase of P, the remaining high temperatures may offset the benefits of higher P due to an increase in evapotranspiration. The ACZ of “Low suitability” is furthermore expanding into areas that were of “High suitability” and “Medium Suitability” for agriculture. This is mainly due to an increase in temperature coupled with decrease in precipitation. To be able to sustain current agricultural yields, these areas would require increased irrigation and maintenance. The overall agricultural productivity is bound to decrease in these areas.

An increase in mean annual rainfall and temperature will only result in an increased agricultural potential in specific locations. In lowlands for example, a relatively lower increase in precipitation may not lead to an increased productivity since the evapotranspiration can potentially offset it. On the contrary, areas of high elevation with a relatively higher precipitation may potentially have an increase in productivity and thus a higher humidity, thus resulting in higher potential yield of crops (Herrero et al., 2010). This is due to the highlands experiencing a lower T due to the difference in elevation, leading to a lower evapotranspiration potential.

ACZ- IV, which has the highest agricultural suitability, is densely occupied by croplands (60%) but at the same time only covers a small in area in Kenya and therefore hosts roughly 26% of the country's total croplands. Despite its high potential for agriculture, this area is not fully utilized. This is mainly due to high population density in those areas which corresponds to a certain percentage of the land occupied by built-up areas. In contrast, ACZ- III, which is the medium suitability zone for agriculture, hosts 46% of the country's croplands with only 30% of the zone being occupied by them. This implies a very low agricultural productivity despite its relatively good potential for agriculture. Thus, areas of "Very high" to "Medium suitability" for agriculture are not being utilized to maximize crop production due to constraints such as population and lack of land-use planning. On that account, the projected ACZ's don't take into consideration how the population may change along with its distribution which will affect the location of croplands.

Main cities of Kenya, Nairobi, Kisumi and Nakuru, are expected to experience a large change in both temperature and precipitation observed in fig 6 and 7, making them quite vulnerable to climate change. According to future population projections illustrated in (Appendix 1), the population can increase up to 91.6 million, which is around 1.7 times higher than the current population. Consequently, climate change coupled with this high increase in population will heavily impact the agricultural sector while also contributing to water stress which in turn will also be detrimental to the agricultural sector.

4.2 Water scarcity

The main water towers or catchment areas are located mainly close to ACZ I and II which are the most suitable classes for agriculture. Majority of the population also lies within these two zones (fig 9). Therefore, it is only justified that majority of the people rely on the water towers as their main water supply as areas of high population density correspond to a higher demand in water due to higher consumption and agricultural needs. This implies that these water towers are crucial for the livelihood and food security of Kenya. According to the projected precipitation change (fig 11), it can be observed that there is a decrease in the overall annual precipitation in high elevation areas which can heavily affect the catchment areas in the future. A study by Mwangi et al. (2020), confirms this study's findings by concluding that climate change will only increase the vulnerability of these water tower ecosystem. Additionally, projected increase in temperature in areas of the water towers will further strain the natural water resources of. Climate change induced extreme weathers affecting the five main water towers may further exacerbate water stress. This can further cause nutrient loss from croplands due to surface runoff and soil erosion, therefore affecting the surface water and its quality (Mulwa et al., 2021; Mwangi et al., 2020). Since irrigation depends mainly on these water sources, the areas that rely on it are expected to be heavily affected in the future as well. National goals to implement more irrigation systems to reduce overreliance of rainfed farming (Rockström & Barron, 2007) may increase water stress on surface water in the future.

4.3 Model validation

The modelled ACZ's in this study is quite simplified and relies mainly on climate, elevation and current cropland location, however, when compared with ACZ's from other studies (Bein, n.d.), despite its complexity, both illustrate a distinct and similar pattern. Furthermore, crop distribution also relies on other factors not included in the scope of this study, such as soil organic carbon (SOC) and -pH ((Kibunja, n.d.) see Appendix.3). This relationship can be seen when comparing this studies findings with soil related research from (Kibunja, n.d.). Areas in this study that have been classified as "Highly suitable" or "Medium Suitable" for agriculture lie mainly in soils that have a lower pH and a higher SOC (Appendix 2). The soil distribution in this particular area, overlying the categorization made in this study, validates its results.

4.4 Recommendations

This section will provide recommendations for policymakers and stakeholders for adaptation strategies that can be employed to improve agricultural practices in Kenya and enhance the sector's resilience to the impacts of climate change and water scarcity:

1. **Agricultural investments (input, services and maintenance) in highlands and areas within close proximity** – To really capitalize on the potential yield increase in the areas (maximizing agricultural productivity)
2. More C_4 plants including maize, sorghum, sugarcane, and millet should be planted in less suitable agricultural zones – In a research by Kurukulasuriya & Rosenthal, (2013) it was discovered that plants classified as C_3—including cotton, rice, wheat, barley, soybeans, sunflower, potatoes, leguminous, woody plants, and the majority of horticultural crops—respond to elevated CO_2 more favorably. According to Kogo et al, (2021) C4 plants are predicted to adapt to greater temperatures better than C3 plants and to use water more efficiently
3. Crop diversification and shading/sheltering or planting of trees – For long-term temperature changes. Studies have shown a low percentage adopting crop diversification could be due to lack of knowledge, skills and finances (Kurukulasuriya & Rosenthal, 2013). Shading/sheltering/tree planting is also a form of soil conservation
4. Implementation of drip irrigation on a larger scale in Kenya – Reduces water use by 30-70%
5. Implementation of laws and regulations for the protection of the 5 main "water towers" of Kenya – It is critical for the security and sustainability of urban water supply and minimization of water scarcity in Kenya. This will also benefit the agricultural sector as it relies heavily on these catchment areas
6. Raise awareness of and/or educate farmers about climate change – Research has shown that educated farmers were more perceptive and knowledgeable about weather patterns than less educated ones, and that they ultimately timed the onset of rainfall as an adaptation choice for the best crop production under rain-fed conditions (Kogo et al., 2022).

4.5 Limitations

One of the main limitations of this study is the CORDEX climate data used. The most recent climate data available was from 2005 and this study uses an average from 1981-2005. It is quite dated compared to the land use data, which is from 2019 and therefore, may not fully capture the climate trends and variability of that of 2019. The data also has a relatively low spatial resolution therefore, fine-scale local features may not be fully captured, leading to potential uncertainties in localized climate projections for Kenya. The climate projections are also subject to uncertainties as they strictly rely on GHG emission scenarios. Therefore, the projections made in this study are not the most realistic representations of climate change.

A second limitation, which is also a major one, is how the climate classes (T & P) were formed. This study used “Natural Breaks” in order to classify both T and P into 5 distinct classes. While other methods would be suitable as well, for this particular study, this form of classification was deemed to fit the best. This form of method was finalized mainly through overlying the cropland layer on the T and P layers and observing which classification method fit best with the pattern of the existing cropland distribution. “Natural Breaks”, for both T and P, followed a clearer pattern with respect to the distribution of croplands. This method, which was then used to model ACZ’s, is therefore quite subjective.

Additionally, the ACZ’s modelled in this study, mainly rely on temperature, precipitation and elevation. However, the modelled ACZ’s for the present took into account population to a certain extent. To elaborate, the categorization of the ACZ’s were mainly based on cropland location and intensity. These areas roughly indicate where the people preferred to grow crops based on where they live (the greater the agricultural suitability, the greater number of people living in that area, or in close proximity to it and vice versa), climatic conditions were not always prioritized. However, for the majority of the area, agriculture was established in areas that were climatically suitable for agriculture, except for certain cases like the “Low Suitability” areas for agriculture near the coast that consisted of a relatively large amount of people residing there. Therefore, the model used in this study does not directly account for population and how it will change in the future. In reality, the ACZ may shift differently. Furthermore, there may be other factors influencing land use practices that are not reflected in the available data and analysis such as other climatic factors, soil, wind, hydrology or terrain.

4.6 Future Studies

Climate change is also expected to increase the frequencies of extreme climatic events such as floods and droughts. Many studies have identified Kenya to be a highly exposed country prone to these events (Herrero et al., 2010.; Kogo et al., 2021; Ochieng et al., 2016). Additionally, soil erosion, land degradation and water logging of crop, exacerbated by an increase in flood intensity will affect agricultural productivity of Kenya, therefore, resulting in reduced yield and increase in food insecurity (WBG, 2021). Therefore, it would be highly relevant for future studies to investigate seasonal variation of climate and of its extremes. The predicted increased frequency of floods and droughts associated with water scarcity will likely affect yield and agricultural productivity, therefore further studies are needed to improve the accuracy of model's predictions. Future studies can also include more variables in the model to refine the ACZ's such as soil fertility, wind etc.

5. Conclusion

In conclusion, this study highlights the impact of climate change on agriculture and water scarcity in Kenya. The projected changes in temperature and precipitation patterns indicate that areas in the western parts of the country will experience greater temperature increases and an overall decreased precipitation. These changes in climate variables have significant implications for agricultural suitability, particularly in the areas classified as the most suitable for agriculture (ACZ-IV). The projected decrease in precipitation coupled with an increase in temperature affects the suitability of this zone and is expected to lead to a decrease in agricultural productivity in the near and far future. Moreover, the study emphasizes the vulnerability of water towers and catchment areas, which are crucial for water supply in Kenya. The projected decrease in precipitation in high elevation areas, coupled with the anticipated increase in temperature, poses a significant threat to these water sources. This, in turn, can exacerbate water stress and impact both the agricultural sector and the livelihoods of the population relying on these water resources.

While the model used in this study has certain limitations, including the use of dated climate data and subjective classification methods, the findings align with other research and soil-related studies, validating the results to some extent. Based on the findings, several recommendations are provided to policymakers and stakeholders to enhance agricultural practices and resilience to climate change and water scarcity. These include targeted agricultural investments, crop diversification, implementation of drip irrigation, and the implementation of laws and regulations for the protection of water towers. Additionally, raising awareness and educating farmers about climate change can help them make informed decisions and adapt their farming practices accordingly. Future studies should further investigate the seasonal variation and extremes of climate change, as well as the impacts of floods and droughts on agricultural productivity. Improved accuracy and understanding of these predictions can aid in developing effective adaptation strategies to mitigate the adverse effects of climate change in Kenya.

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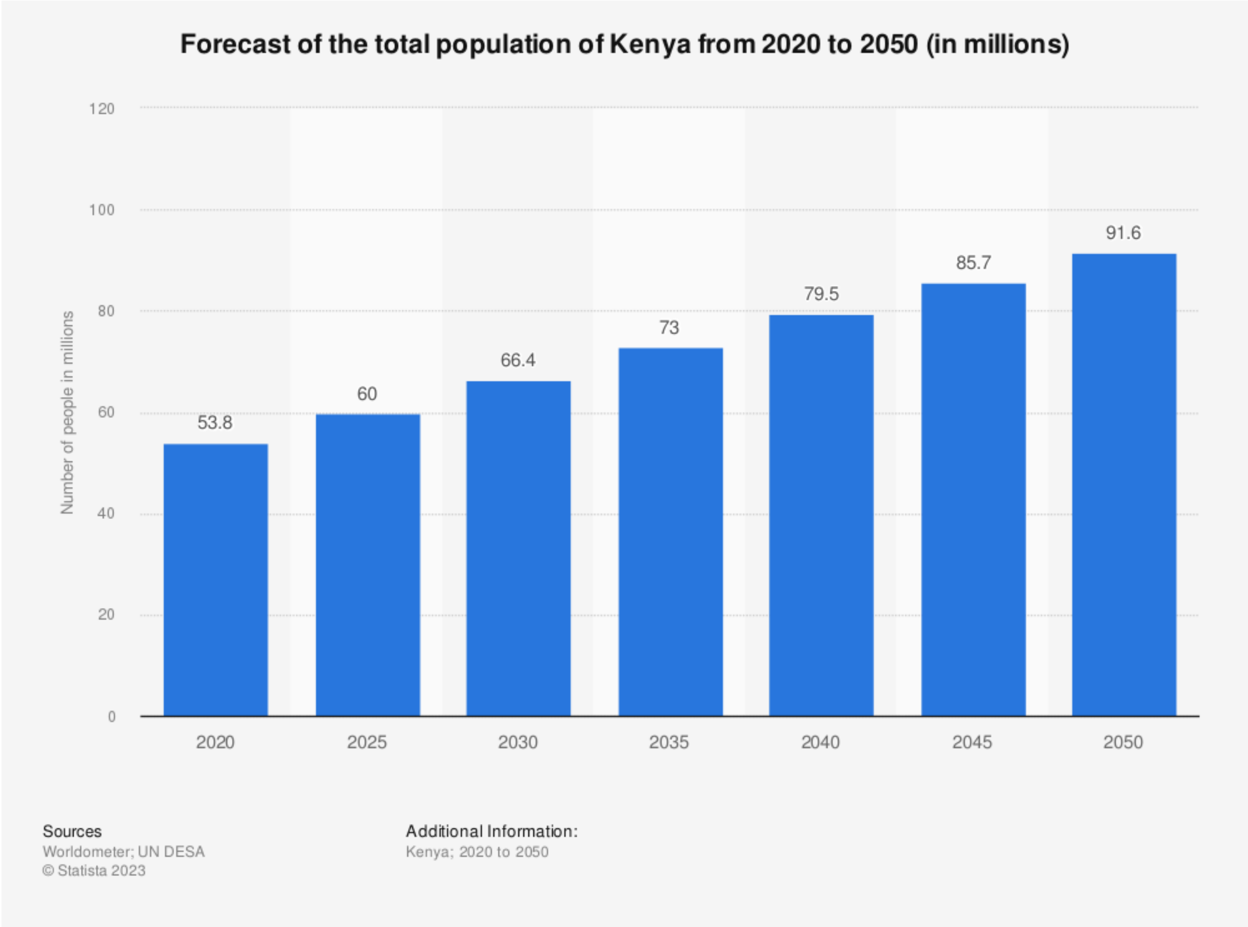
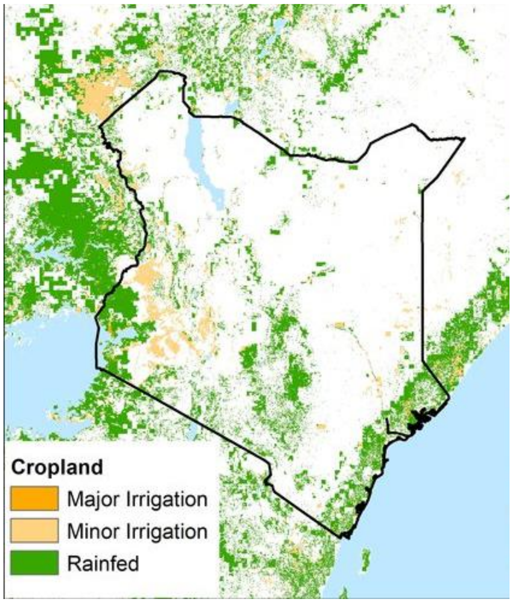
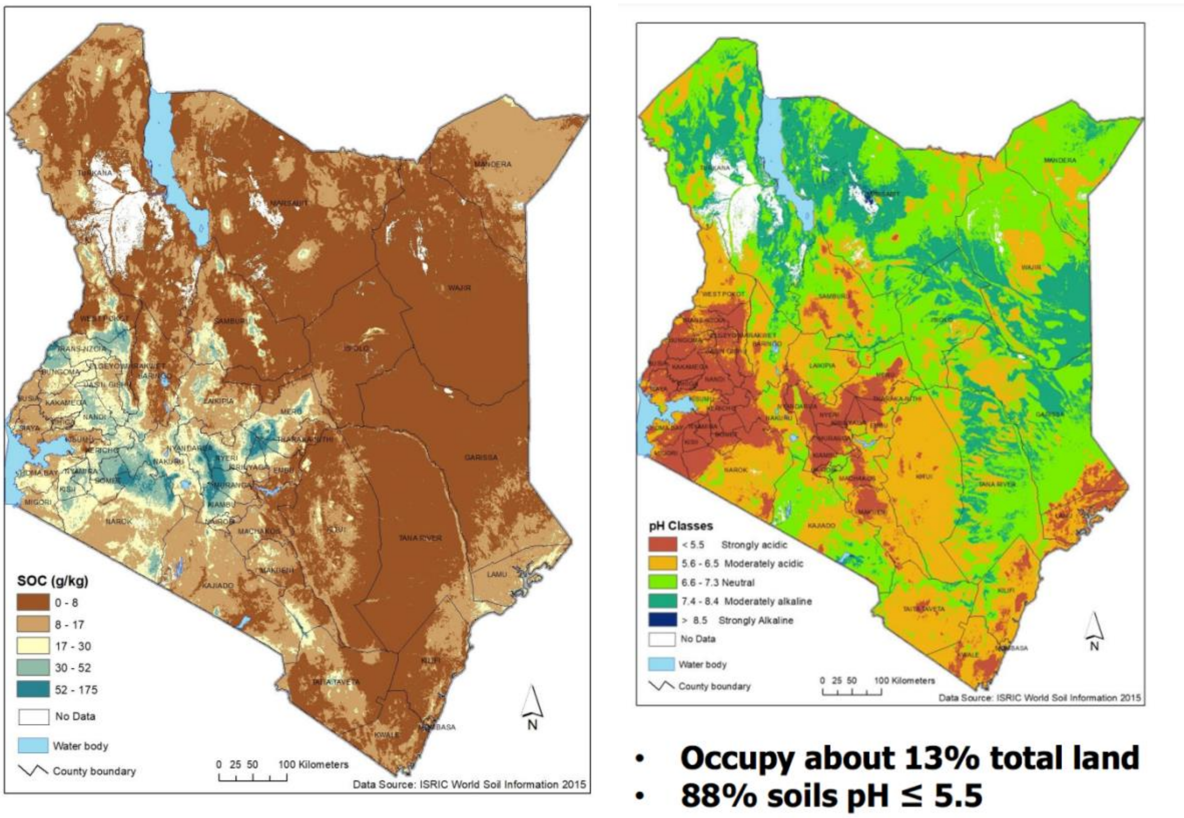
Appendix



Appendix 1. Forecast of total population in Kenya

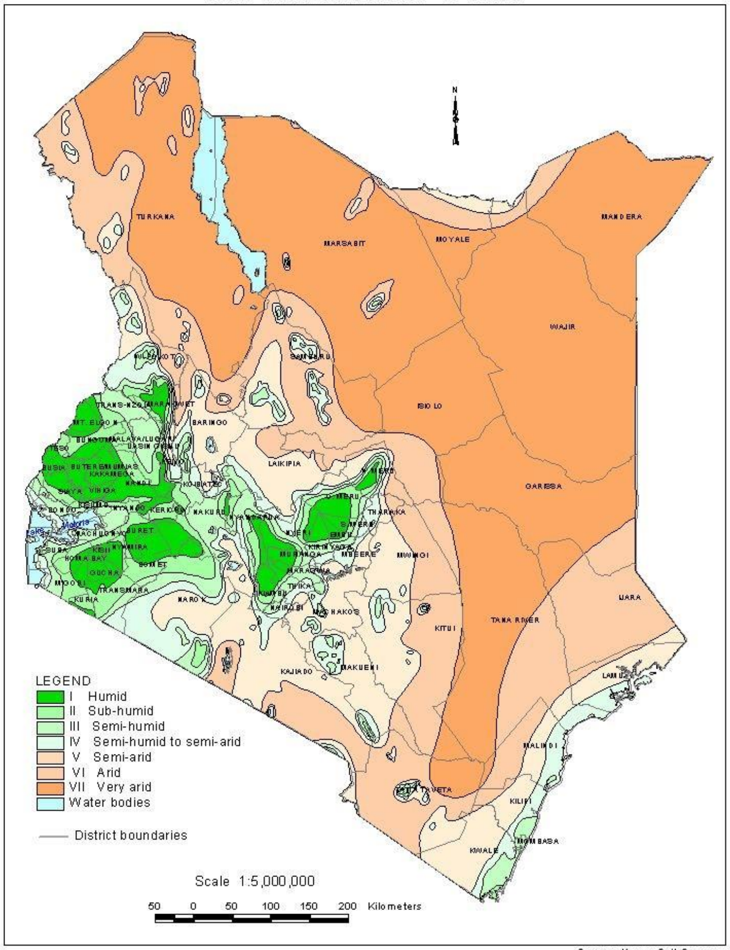


Appendix 2. Cropland map showing areas of irrigation and rainfed (Miller et al., 2021)



Appendix 3.Soil Organic Carbon and pH map of Kenya (Kibunja, 2018)

AGRO-CLIMATIC ZONE MAP OF KENYA



Source, Kenya Soil Survey

Appendix 4. ACZ map pf Kenya for model(Bein, n.d.)