Future crop suitability assessment and the integration of Orphan crops into Kenya's food systems

Masters Dissertation

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Abstract

Climate change is seen to be playing an increasingly key role in determining the level of food security within Kenya. In 2020, around 3.1 million people in the country faced acute food insecurity as a result of excessive rainfall, flooding and drought. There has also been a concentration of research on major crops, such as maize and common bean. This study, therefore, seeks to contribute to the research gap in future projections of crop suitability for major and minor crops in Kenya.

Temperature and rainfall data, downloaded from CORDEX, from four statistically downscaled Global Climate Models (GCMs) under the Representative Concentration Pathways (RCP) 8.5 and 4.5 were used to run the Ecocrop model. The output was the suitability index spatially plotted over the country for maize, finger millet, common bean, broad bean and sweet potato, within three time periods: historical (1980-2009), near term (2010- 2039) and mid-century (2040-2060). To further understand the influence soil pH has on the climate suitability of these five crops, QGIS was used to overlap Ecocrop suitability outputs and Soilgrids soil pH rasters.

CORDEX projections indicated a 2°C- 2.5°C and 1°C rise in temperature under RCP8.5 and 4.5 respectively, and rainy seasons becoming more intense and shorter. The suitability index of maize is projected to have a slight increase (20%) during the long rains, by the end of the century under RCP8.5. Along the RCP4.5 pathways, there is a greater increase in suitability for maize in counties along the coast and western Kenya. Results also project a significant suitability increase (50%) of the orphan crop- broad bean- during the dry season. The spatial distribution of suitability is widespread within many arid and semi-arid counties. This presents an opportunity to integrate legumes such as broad bean into the cropping system within a crop rotation with maize. This form of adaptation would help ease the pressure on the production of staple crops since suitability for maize and common bean is projected to decrease during the short rains.

Soil pH results indicated the dominance climate has on determining overall suitability. For instance, pH suitability of finger millet was achieved in majority of the counties however, climate suitability does not favour the planting of this crop. For sweet potato, there is

optimum pH and climate suitability, however, it is not greatly distributed around the country. Despite the low spatial distribution, these small areas of sweet potato production can also contribute to better food security in these counties

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AOCC	African Orphan Crops Consortium
ASAL	Arid and Semi-Arid Lands
ASL	Above Sea Level
CIP	International Potato Center
CSA	Climate Smart Agriculture
CORDEX	Coordinated Regional Downscaling Experiment
ENSO	El Niño-Southern Oscillation
FAO	Food and Agriculture Organization
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
PREC	Precipitation
RCP	Representative Concentration Pathway
SIV	Suitability Index Values
SSA	Sub-Saharan Africa
SST	Sea Surface Temperature
TAS	Average Temperature
TASMIN	Average Minimum Temperature

Chapter One: Introduction

The increasing global population is met with a drastic intensification of agriculture aiming to meet the nutritional demands of 9.15 billion people by 2050 (Alexandratos & Bruinsma, 2012; McKenzie & Williams, 2015). Agricultural intensification can have both favourable and unfavourable consequences depending on how it is done (McKenzie & Williams, 2015). Often, the sustainability of the food production systems is questioned. This is especially true in Sub-Saharan African, whereby 33% of the population are undernourished, with over 60% of this population being in East Africa (Khan et al, 2014; McKenzie & Williams, 2015). Assessing the suitability of a crop is a vital component in maintaining a sustainable food production system under future climate as changes in crops geographic distribution can be foreseen.

This chapter provides an overview of the major themes that are encompassed in the suitability study of major and minor crops grown in Kenya. These themes include Kenya's economy, population and livelihoods which all form a base for the agricultural sector in the country. It also focuses on the climate systems and the change experienced in Kenya which plays a role in the level of food insecurity. This chapter also explores the impact soil pH has on crop suitability as well as orphan crops and their ability to alleviate malnutrition and hunger.

1.1 Background

1.1.1 Kenya's economy, livelihoods and population growth

Agriculture is a key component in Kenya's economy, contributing to 27% of GDP as well as providing employment to over 40% of the population (FAO, 2019). The main food crops are maize, beans and potatoes, which are traded locally. Maize is considered the principal staple crop in Kenya and is found to be grown in 90% of all Kenyan farms (FAO, 2009; FAO, 2011). Smallholder farming systems dominate the agriculture sector, with household-level subsistence accounting for 75% of national food production (GDC, 2017). These farming systems are often characterised by the lack of access to inputs, irrigation systems or knowledge on sustainable technologies. This reduces the ability of such farmers to cope with shocks and stresses associated with climate change. Rapid population growth in the country is putting a constant strain on the agricultural sector and is predicted to continue in the future, as Kenya's population is projected to reach about 85 million by 2050 (World Bank, 2010).

1.1.1.1 Major crops in Kenya

Staple crops are an important source of food security and income generation for the majority of households in Kenya. The main food crops in Kenya include maize, rice, wheat, common bean and potato (USAID, 2010). However, these major crops grown in Kenya are insufficient to meet the demands each year. Therefore, Kenya relies on imports for example, in 2020, about 277,300 tons of maize, the majority of which came from Uganda and Tanzania, was brought into the country (Ministry of Agriculture, 2021). The crops covered in this study are maize and common bean.

Maize (*Zea mays*)

Maize is Kenya's main staple food crop and is commonly consumed as ugali, which is a porridge made from maize flour. Total land is under maize production is approximately 1.5 million hectares, which equates to 40% of the total crop area in the country. The annual average production is around 3 million metric tons (KARLO, 2021). Maize has a high carbohydrate level and provides more energy than many other cereals, such as finger millet (Table 1). This is an essential aspect of a staple food since it can provide people with enough energy at a low cost. It lacks many vitamins and minerals that are available in finger millet (Singh & Raghuvanshi, 2012). This is a contributing factor to the high levels of vitamin A, iron and iodine deficiency amongst many Kenyans (Muthoni & Nyamongo, 2010).

Common bean (*Phaseolus vulgaris*)

Kenya is the 7th largest producer of common beans, globally, with the per capita consumption being the highest in Africa, at around 66g per year (USAID, 2010). Like broad bean, common bean is high in protein (18.8g/100g) and energy content. These beans also provide iron, potassium and magnesium while containing a low fat content.

1.1.2 Climate change, variability and Greenhouse gas emissions

Climate change is adversely affecting Kenya's agriculture sector, through increasing temperatures, erratic rainfall and drought. This has a prominent effect on 80% of the country, which is classified as Arid and Semi-Arid Lands (ASAL) (Omoyo et al., 2015). As Greenhouse

Gas (GHG) emissions continue to increase, climate change persists to be exacerbated. If action is not taken towards reducing GHG emissions, projected future climates in Kenya indicate a 3°C temperature increase by 2060, increased inter-seasonal rainfall variability and increasingly severe droughts and flooding events (World Bank, 2017; Niang et al, 2014). With Kenyan agriculture being 98% rainfed, it tends to be highly sensitive to these changes in temperature and rainfall (USAID, 2018). For instance, maize has been demonstrated to be particularly susceptible to climate change, with each day spent above 30°C reducing the final yield by 1% under ideal rain-fed conditions and by 1.7% under drought conditions, which occur when there is a water shortage (Lobell et al, 2011). This impact on maize is evident in Kenya, whereby studies have shown a strong positive correlation between rainfall, temperature and maize yields in districts that are part of ASALs (Kariuki et al., 2018).

Since cumulative GHG emissions are a key driver of climate change, the Intergovernmental Panel for Climate change (IPCC) has developed Representative Concentration Pathways (RCPs) based within the Fifth Assessment Report (AR5) (Knutti & Sedlácek, 2013). These RCPs are the prescribed pathways for GHG and aerosol concentrations, coupled with land-use change, which result in a set of broad climate outcomes and are characterized by the radiative forcings produced by emissions till the end of the 21st century (Figure 1).

The RCPs consist of 4 main pathways: RCP 2.6, 4.5, 6 and 8.5, whereby the 8.5 represents the climate pathways with minimal effort to reduce emissions and would result in a 4°C rise in temperature, globally, by 2100, while the RCP 2.6 projects the lowest radiative forcing, at approximately 3 W/m^2, due to reduced emissions (Van Vuuren et al, 2011). RCP pathways are important, such that they provide more detailed and better-standardized greenhouse gas concentration inputs for running models, such as Ecocrop. Therefore, outputs from this study can be easily shared between multiple disciplines.

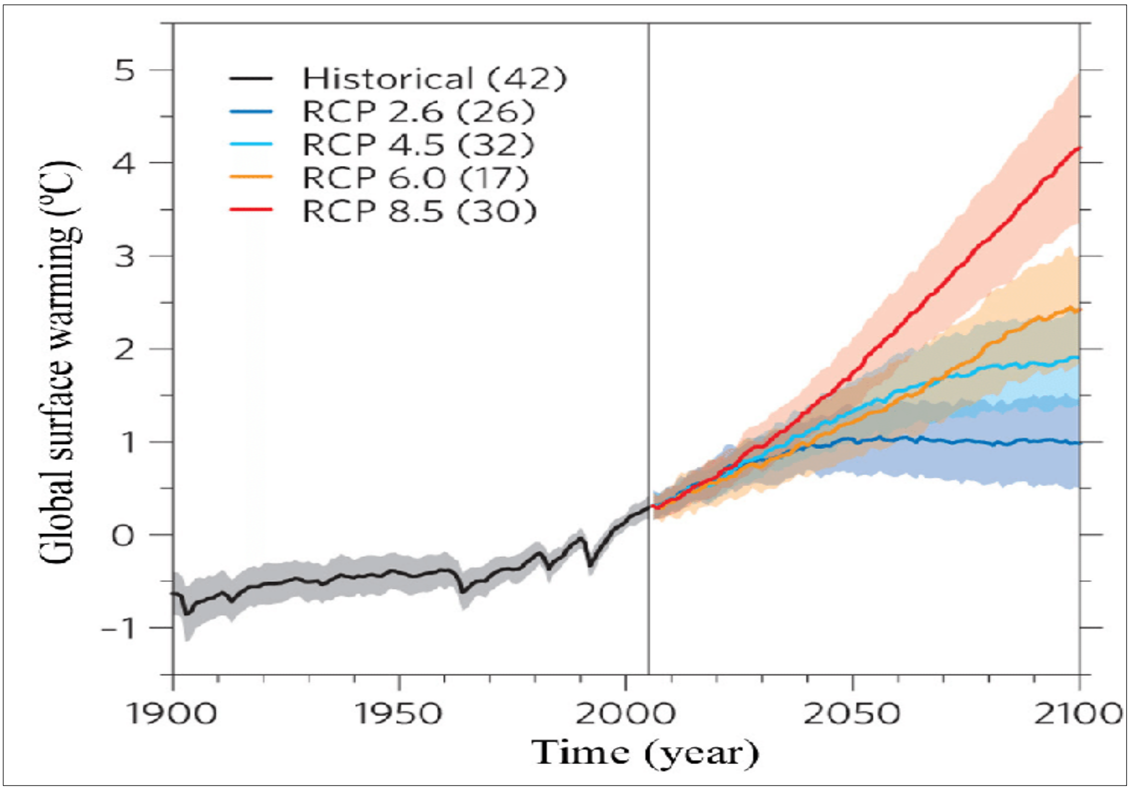


Figure 1: Global surface warming indicating mean temperatures and degree of uncertainty (shaded area). The number of models is given in brackets.
Source: Knutti & Sedláček (2013)

1.1.3 Soil pH, soil health and climate change

Soil pH is the measure of the acidity or alkalinity of soil represented by the H^+ activity in the soil solution that is in a dynamic equilibrium with a negative charged solid phase (Rengel, 2011). Soil pH is a good indicator of soil health as it highly influences the capacity of soil to store and supply nutrients, host pathogens and cause plant diseases (Rengel, 2011; Slessarev et al, 2016; Zhang et al, 2019). pH ranges between 0 and 14, with alkaline soils with a pH higher than 8 and acidic soils below 7.

At a global scale, soils from different climates have distinct soil pH since precipitation and potential evapotranspiration control variations at a global and regional scale (Slessarev et al, 2016, Cheng et al, 2014) such that alkaline soils, with a high pH, are commonly found in arid climates and acidic soils in humid regions. This is explained by a negative correlation between soil pH and mean temperature and precipitation, such that soil pH presents a downward trend when precipitation increases (Cheng et al 2014; Chytrý et al, 2007). Increased precipitation results in enhanced leaching of basic cations, which can lead to soil acidification (Rengel, 2011). Within agricultural systems, greater acidification would require the application of large amounts of lime to improve the soil pH, however, this is often associated with significant transportation and costs. The absence of sufficient lime application will lead to soils becoming unproductive and unsustainable to crop on (Rengel, 2011).

Due to this relationship between climate and soil pH, climate change can have a significant impact on future soils. Increased acidification would arise in regions where higher rainfall is projected while increasing temperatures coupled with a decrease in rainfall in arid regions would create more alkaline soils. In addition, increased evaporation of groundwater would result in salt accumulation in the soil (Gelybó et al, 2018).

1.2 Food security and the role of Orphan crops

1.2.1 Food security in Kenya

With maize and other staple foods being sensitive to changing climates the state of food security within the country has been worsening in Kenya. During the World Food Summit in 1996, food security was defined as "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO 1996), and remains articulated around four dimensions of food availability, accessibility (physical and economic), stability and utilization (Battersby & Haysom, 2018). By this definition, 3.1 million people in the country were estimated to have faced acute food insecurity in the year 2020 (US AID, 2019). This comes as a result of excessive rainfall and flooding, as well as acute drought which highly affects staple foods such as maize. This is coupled with a rapidly growing population for which the agriculture sector cannot meet the demands due to low productivity at the farm level (US AID, 2019). Relying solely on the intensified agriculture crop system, which focuses on the most globally significant crops, leaves food systems highly vulnerable to projected climates.

1.2.3 The importance of Orphan crops

A considerable amount of literature is dedicated to enhancing the productivity of cash crops or main staple crops, however, orphan crops have received little interest in comparison within past decades (Handschuch & Wollni, 2013). The term 'Orphan crops', also known as 'underutilized crops', reflects the relatively limited attention of research and development to such crops, despite the vital role that orphan crops play in enhancing food security and nutrition in developing countries such as Kenya (Tadele, 2019; Bvenura & Afolayan, 2015). Tackling the challenges of world hunger, malnutrition, starvation and other socio-economic issues requires a paradigm change to make substantial progress. Orphan crops, such as millets, cassava, cowpea, Bambara groundnut and tef have the potential to feed millions of people in Africa, as they are already adapted to thrive in local conditions and contribute to sustainable food systems under climate change conditions (Madhaudhi et al, 2019, Tadele, 2019). Previous studies have shown that orphan crops also have a greater threshold in tolerating harsh climate conditions, compared to cash crops such as maize and rice. For instance, finger millet, pearl millet and tef are found to be extremely tolerant to moisture deficits (Haussman et al., 2012; Tadele, 2016).

The African Orphan Crops Consortium (AOCC) has listed sweet potato, varieties of millet such as fonio and finger millet and broad bean amongst the 101 African orphan crops (http://africanorphancrops.org/meet-the-crops/). These were identified based on a participatory manner as being important for supporting consumers' diets and farmers' incomes in Africa.

Sweet Potato (*Ipomoea batatas L.)*

The cultivation of sweet potato is widespread within Africa, with the perennial vine grown throughout East Africa primarily within subsistence farming systems. Sweet potato has several uses, varying from the roots being consumed after boiling, roasting or processing it into flour, starch and animal feed. Sweet potato has a short maturity period of three to seven months and is capable of growing with minimal fertilizer inputs. They are also adaptable to different agro-ecological zones, ranging between 0 and 2100m above sea level (KALRO, 2019). Sweet potato has several nutritional benefits as well as being a good source of energy (359 kcal/100g) (Table 1). This source of energy and keeps vital organs, such as the heart, brain and kidneys functioning.

Finger millet (*Eleusine coracana*)

Millets are cultivated as cereals in arid and semiarid regions of the world with Pearl millet *(Pennisetum glaucum),* Common millet *(Panicum miliaceum)* and Finger millet

(Eleusine coracana) are the most common varieties grown in Kenya. Of these, Finger millets and Fonio are classified as orphan crops. Finger millet is said to originate in East Africa, within

Table 1: Nutritional value per 100g serving for maize, finger millet, common bean, broad bean and sweet potato. Source: USDA (2020)

					
	Maize	**Finger millet**	**Common bean**	**Broad bean**	**Sweet potato**
Energy (kcal)	365	72.6	342	341	359
Protein (g)	9.42	7	18.8	26.1	1.6
Total Lipids (Fat)(g)	4.74	5.2	2.02	1.53	0.1
Carbohydrate (g)	74.3	72	64.1	58.3	20.1
Fibre (g)	2.7	1.2	3.4	8	3

the Ugandan highlands and in Ethiopia (Achaya, 2000). Like maize, finger millet is grown to be processed into flour that can be used in making porridge, flatbread or 'chapatti', with biomass being used as animal feeds. Finger millet (Wimbi in Swahili) porridge is a popular food in Kenya known for its nutritional benefits (Table 1) in terms of daily protein (7g/100g), carbohydrates (72g/100g) and dietary fibres (1.2g/100g). It is also becoming a popular option for baby food due to its high calcium content (Devi, 2014; Singh & Raghuvanshi, 2012).

Broad bean *(Vicia faba)*

Broad bean, also known as fava or faba bean, is a legume within the Fabaceae family. It is widely grown as a cover crop, for human consumption and as an animal feed. Broad beans have a very long history of cultivation and are believed to be part of the eastern Mediterranean diet around 6000 BCE (Kosterin, 2014). Broad beans are considered as one of the most important legumes in Ethiopia, a neighbouring country of Kenya, where it is used as a replacement for peas to make flour. It is especially rich in dietary fibre (8g/100g), protein (26.1g/100g), manganese, phosphorus and iron.

1.3 Thesis Aim and objectives

This study aims to assess the future climate suitability of cultivating major and minor crops under different climate change scenarios within different agroecological zones in Kenya.

The objectives of this study are to:

1. Identify the extent of climate change, in terms of rainfall and temperature within counties in Kenya;
2. Simulate the spatial suitability of maize, finger millet, common bean, broad bean and sweet potato;
3. Evaluate the seasonal suitability of maize, finger millet, common bean, broad bean and sweet potato;
4. Compare the climate suitability of the 5 crops under RCP 8.5 and RCP 4.5;
5. Quantify the spatial extent of soil pH in determining suitable growing area for maize, finger millet, common bean, broad bean and sweet potato.

Based on the outcomes of achieving the aim and objects of this study, the following research question is devised: "How can these three orphan crops used in the study be integrated into Kenya's food systems in order to improve the state of food security amongst the population".

This thesis is divided into six chapters. After the introduction in Chapter one, a literature review is provided in Chapter two. It includes a review of the current literature about Kenya's climate systems, the impact of climate change on the country, the state of food security, the influence of soil pH on crop production and crop suitability models. Within Chapter three, the data and methods used to achieve the aim and objectives of this study are described. This contains information about the climate data obtained from CORDEX and the soil rasters downloaded from SoilGrids. An explanation of how the Ecocrop model is used to generate suitability scores is also provided. An in-depth analysis of the results are presented in Chapter four and a discussion based on these results are available in Chapter five. Finally, Chapter six offers the key findings and outlines reflections on future avenues for research.

Chapter Two: Literature

Kenya is characterized by a tropical climate with an annual mean temperature of 18°C and variable levels of precipitation throughout the year (Kottek et al., 2006). The IPCC projects a 1.2-2.2°C temperature increase, increased inter-seasonal rainfall variability and more prominent droughts and flooding events (IPCC, 2014). This study was highly motivated by the current levels of food insecurity in Kenya and future projections likely to worsen with climate change. For these reasons, it is becoming vital to understand the impacts that future climate is having on crops and consequently on food security. This chapter provides an overview of how food security and food systems are being impacted by climate stress and how this may be exacerbated in the future due to changing climate drivers in Kenya. Furthermore, literature on the impact soil pH has on crop production is provided as well as the role orphan crops could potentially play in improving food security. This chapter concludes by reviewing crop models as a means of simulating future crop suitability.

2.1 Food systems and climate change

2.1.1 Food security

Sub-Saharan Africa has shown an unceasing challenge of food security and sustainable agriculture (Rarieya & Fortun, 2010), with no substantial improvements since the 1996 Rome World Food Summit (WFS). As of 2018, 26.4% of the global population, accounting for about 2 billion people, experience moderate to severe levels of food insecurity (FAO, 2019). This came as a considerable increase from the 2009 statistics, which indicated an estimate of 923million people globally that were food insecure (FAO, 2008). The majority of this population is concentrated in Sub-Saharan Africa and Asia, with the former being described as a host to the major 'poverty and hunger hotspots' (Sanchez et al., 2005; Rarieya & Fortun, 2010). For instance in Kenya, as of 2006, a third of the population, which is an estimated 10.6 million people, suffered from chronic poverty (FAO, 2006a).

The food insecurity problem is compounded by global climate change and associated changes in precipitation, temperature and sea levels (Rarieya & Fortun, 2010; Muebe et al., 2018; Macoloo et al., 2013; Samwel et al., 2018, Ericksen et al., 2011). Extreme events have the capacity to affect all four pillars of food security: food availability, accessibility, utilization and stability. Food availability can only be achieved when sufficient food is produced and well distributed (Gregory et al, 2005) and access to food is characterised by the ability to purchase food or being able to consume the food bought (Gregory et al, 2005). Providing food that meets its nutrition and health quota whilst being able to consume it in a socially appropriate manner will determine whether food utilization can be achieved (Battersby & Haysom, 2018). Food stability is defined as the ability of a society to access food in the long run with certainty (Battersby & Haysom, 2018). Climate change potentially affects each of these four pillars, for instance, increasing temperatures may influence the length of a growing season while changes in precipitation potentially affect crop production. These thereby affect the availability of crops within the markets (Rarieya & Fortun, 2009; Songok et al., 2011). The repercussions of the scarcity of food in the market lead to higher prices, thereby altering the ability of a poor population to have access to food (Songok et al., 2011; Adger et al., 2003). Changing climates also increases the likelihood of pests, weeds and diseases, which prompts farmers to apply higher rates of pesticides and herbicides. Therefore, an increase in chemical use compromises the utilization of food since these chemicals are said to have negative implications for the human body (Sharma & Singhvi, 2017). Finally, climate change potentially affects food stability, since the uncertainties presented with future climate leads to farmers being unable to plan their crop production in the long run.

2.1.1 Agricultural systems and adaptation

Temperature and rainfall are crucial in crop production and are often correlated (Ochieng, Kirimi & Mathenge, 2016; Hoffman, Kemanian, & Forest, 2018), however, many studies done in East Africa focus on the effects of one of these variables in isolation. For instance, Oremo (2013) primarily investigated the impact of rainfall on maize yield and found a strong positive correlation between the two. However, due to the intertwined nature of rainfall and precipitation, the inclusion of just one of these variables would lead to omitted variable bias (Ochieng, Kirimi & Mathenge, 2016). A more extensive study was conducted using cross-sectional data on soil, climate, hydrological and household-level data to assess the impact of climate on net returns of crops. Results of a seasonal Ricardian model indicated a non-linear relationship between revenue and temperature and a linear relationship between rainfall and revenue (Kabubo-Mariara & Karanja, 2007; Hoffman, Kemanian, & Forest, 2018). However, when considering yield and revenue, the area of land cultivated must be considered. For instance, Herrero et al. (2010) recognised that the main reason for the increase in production of crops, especially maize, was due to the increased productivity and increased cultivated land. These results, do not stem from adaptation and mitigation measures and therefore reflect a lack of inputs, services and market environments.

Results from studies investigating future crop production (Herrero et al., 2010; Ramírez Villegas, Jarvis & Läderach, 2013; Ramírez Villegas & Thornton, 2015; Kogo et al., 2019) project an overall country-wide loss in the production of staple foods. For instance, outcomes from an Ecocrop simulation of sorghum indicated a 50 to 80% decrease in the suitability area within south eastern Kenya (Ramírez Villegas, Jarvis & Läderach, 2013). Furthermore, Kogo et al. (2019) used the MaxENT model and projected a decrease of moderately suitable areas of 14.6 – 17.5% for maize. Such outcomes provide evidence for the need for Climate-Smart Agriculture (CSA).

CSA is a concept developed by FAO and is "an approach for transforming and reorienting agricultural systems to support food security under climate change" (Lipper et al., 2014) in order to achieve sustainable agriculture under climate change (FAO, 2013). The underlining objectives of CSA are: (1) sustainably increasing agricultural productivity and incomes, food security and development; (2) adapting and building resilience to climate change; and (3) developing prospects to reduce GHG emissions from agriculture (FAO, 2013). CSA can be implemented at a farm level; with the aim of strengthening livelihoods and food security; and at a national level; to implement policies, technology and finances to support the adaptation and mitigation of climate change (Williams et al., 2015). Outcomes from this study can inform decisions of how and where to sustainably increase productivity through growing crops in more suitable areas which allows small scale farmers to adapt to climate change. These methods of CSA has the potential to improve the state of food security within Kenya.

2.2 Climate drivers and climate change

It should be recognized that for the development of effective agricultural adaptation responses to climate change, there should be a greater representation of the climate drivers that impact agriculture (Howden et al., 2007). This is due to each driver having a prominent effect on climate during different times of the year. In Kenya, the main climate drivers include the Intertropical Convergence Zone, El Niño-Southern Oscillation and the Indian Ocean Dipole.

2.2.1 Intertropical Convergence Zone (ITCZ)

The most important climatic element in the tropics is rainfall due to the heavy reliance on rainfed agriculture (Shisanya et al., 2011). Rainfall seasonality in Kenya is experienced as a bimodal system: March to May (‘long rains’) and October to December (‘short rains’) (Ogwang et al., 2015; Merchant et al., 2005; Nicholson, 2018). This coincides with the passage of the Intertropical Convergence Zone (ITCZ) during its north-south displacement (Ogwanga et al., 2015; Nicholson, 2018). The ITCZ is defined as “an east-west oriented low-pressure region near the equator where surface northeasterly and southeasterly trade winds meet” (Yan, 2005). This creates a belt of low-pressure systems that facilitate heavy rainfall and is responsible for 32% of global precipitation (Kang et al., 2018). In January, the ITCZ propagates south of the equator and shifts to the northern hemisphere in July (Nicholson, 2017).

Climate change is having a considerable impact on the ITCZ (Byrne & Schneider, 2016). The earth’s atmosphere has been experiencing a warming effect due to the increase in anthropogenic activities within the past decade. Burning of fossil fuels, deforestation and land-use changes are instances of human activities that have resulted in the rapid accumulation of GHGs within the atmosphere. These gases, such as carbon dioxide, methane or nitrous oxides, trap heat, thereby creating a greenhouse effect, leading to a general warming of the earth’s atmosphere (Solomon et al.,2007). Changes in global temperature and radiation budget have shown an impact on the width and the strength of the ITCZ, such that the zone has been narrowing and strengthening in the core of the ascent regions, reducing the ratio of the areas of upward motion to downward motion in the tropics (Byrne & Schneider, 2016; Byrne et al., 2018). This has the potential to reduce precipitation on the margins of the tropical convection regions while increasing rainfall within the ITCZ (Byrne & Schneider, 2016), leaving Kenya vulnerable to extreme events such as droughts and flooding.

2.2.2 El Niño-Southern Oscillation and the Indian Ocean Dipole.

Several studies (Ogallo, 1988; Nicholson, 1996; Indeje, et al., 2000; Shreck & Semazzi, 2004; Bowden & Semazzi 2007; Muhati et al., 2007) have shown the correlation results between the El Niño-Southern Oscillation (ENSO) and rainfall variability in Kenya. ENSO plays a significant role in East Africa, in determining monthly and seasonal rainfall in the country, whereby during an El Niño phase, Kenya experiences flood events while the La Nina phase brings about droughts (Ogwang et al., 2018). Upcoming research has also provided evidence of the Indian Ocean Dipole (IOD) having an overwhelming influence on Kenya's short rains as compared to that of the ENSO (Conway et al., 2007; Ogwang et al., 2018; Owiti et al., 2008). The IOD refers to the fluctuations in Sea Surface Temperatures (SST) in the Indian ocean. The IOD experiences a positive phase and a negative phase. During the positive phase, the SST drop in the south-eastern part of the Indian ocean and is counteracted by a rise in SST off the east coast of Africa. This phase brings about greater rainfall and thereby a greater chance of flooding events in Kenya. Inverse conditions exist during a negative IOD phase, bringing drought conditions to the country (Marchant et al., 2006; Conway et al., 2007).

Climate change is affecting both, the ENSO and IOD and resulting in dire consequences as a result of an increase in extreme climate in Kenya. Model simulations forced by scenarios of high greenhouse gas emission project that the frequency of extreme positive IOD events will increase by up to a factor of three. This is due to faster warming in the western than eastern equatorial Indian Ocean, thereby weakening westerly winds and eastward oceanic currents (Cai et al., 2014). Global climate model studies also reveal that as global temperatures increase due to the rise in GHGs, the mean state of ENSO will shift towards a permanent El Niño phase (Yeh & Kirtman, 2006).

2.2.3 Reduction of Greenhouse Gases

Future climates are simulated by General Circulation Models (GCM) using climate change scenarios introduced by the IPCC (2014) Fifth Assessment, which are defined by RCP 2.6, 4.5, 6 and 8. The RCP4.5 scenario represents a future where climate policies limit and achieve stabilization of greenhouse gases to 4.5 W m-2 by 2100, while the RCP 8.5 scenario is the "business-as-usual" scenario, where greenhouse gas emissions remain high due to the absence of climate change policies (IPCC, 2014). Despite RCP4.5 not being the most desirable scenario, in comparison to RCP2.5, it remains a viable goal that can be achieved and would result in substantial benefits over the RCP8.5 scenario. For instance, a study projected the global future frequency of extreme climate events is greatly reduced through mitigation. In terms of reduced changes in 1-day heat extremes, by 2075, it was projected that 95% of land regions would experience a 1°C benefit under RCP4.5. 50% of land areas would benefit by at least 2°C under the lower emission scenario (Tabaldi & Wehner, 2016). Within Kenya, rainfall is projected to increase in areas such as the Tana river basin over the remainder of the twenty-first century, with a greater rise under RCP8.5 than RCP4.5. Therefore, under RCP8.5, there are greater chances of flooding events (Muthuwatta et al., 2018).

Prominent efforts to create climate change policies to reduce GHG include the Paris Agreement. Countries that are part of this agreement committed to keeping global temperature increase below 2°C compared to pre-industrial levels, and strive to limit it to 1.5°C (UNFCCC, 2015). Long-term policy goals are to achieve peak global emission in the near future and to reach zero net emissions in the second half of the century. In order to accomplish this, Parties of the agreement are required to prepare Nationally Determined Contributions (NDCs), outlining their efforts at emissions reductions, based on adaptation, mitigation, technological, financial and capacity-building support (UNFCCC, 2015). Kenya's nationally determined contribution towards the Paris agreement is to target a 30% emission reduction by 2030 through means such as low carbon and efficient transportation systems, increasing of renewables in the electricity mix of the national grid and encouraging Climate-Smart agriculture (CSA) (Ministry of Environment and Forestry, 2020)

2.4 Soil pH

Soil is referred to as being alkaline (basic) neutral or acid, depending on their pH values on a scale from 0 to 14. Soils with a pH between 4 and 5.5 have a strong acidity level, while 5.5 to 7 is medium/slight acidity. pH values greater than 7 indicate alkaline soils, with a range between 8.5 and 10 being considered as strongly alkaline (Roques et al., 2013). pH is a logarithmic function, therefore, each unit on the pH scale is ten times less acidic (more alkaline) than the value below it (McCauley, Jones & Jacobsen, 2009).

2.4.1 The effect of pH on nutrient availability

Soil pH is often considered to be the "master variable" amongst soil parameters (Penn & Camberato,2019; Neina, 2019) since it plays an intricate role in determining the availability and efficiency of a crops intake of nutrients as well as its compounding effects on chemical reactions. Thus, soil pH is a yield-limiting factor and a long-term management concern (McCauley, Jones & Jacobsen, 2009; Kgopa, Moshia & Shaker, 2014; Neina, 2019). Nutrients can be affected in different ways. Taking phosphorus (P) as an example, which is vital to plant growth and is involved in several key plant functions, including photosynthesis, nutrient movement within the plant, energy transfer and the transformation of sugars and starches(Blevins, 1999). The optimum phosphorus is available to plants around a pH of 6.5 (Figure 2). In high pH (7.5 to 8.5) soils, there is typically excess calcium, which then binds to produce calcium phosphate ($Ca_3(PO_4)_2$) which is insoluble in water, rendering it plant-unavailable since it can not be absorbed (Penn & Camberato,2019). A similar situation occurs when soil pH is low (5.5 to 4) and there are high levels of heavy metals present(figure 1), which results in phosphate binding with aluminium and can not be used by the plant (Penn & Camberato,2019).

Soil pH also contributes to determining the cation-exchange capacity (CEC) of the soil. CEC is a measure of the soil's ability to retain and supply nutrients to a crop. The higher the CEC, the higher the negative charge and the more cations that can be held. However, at a low pH, hydrogen ions displace other exchangeable cations from the soil (McCauley, Jones & Jacobsen, 2009).

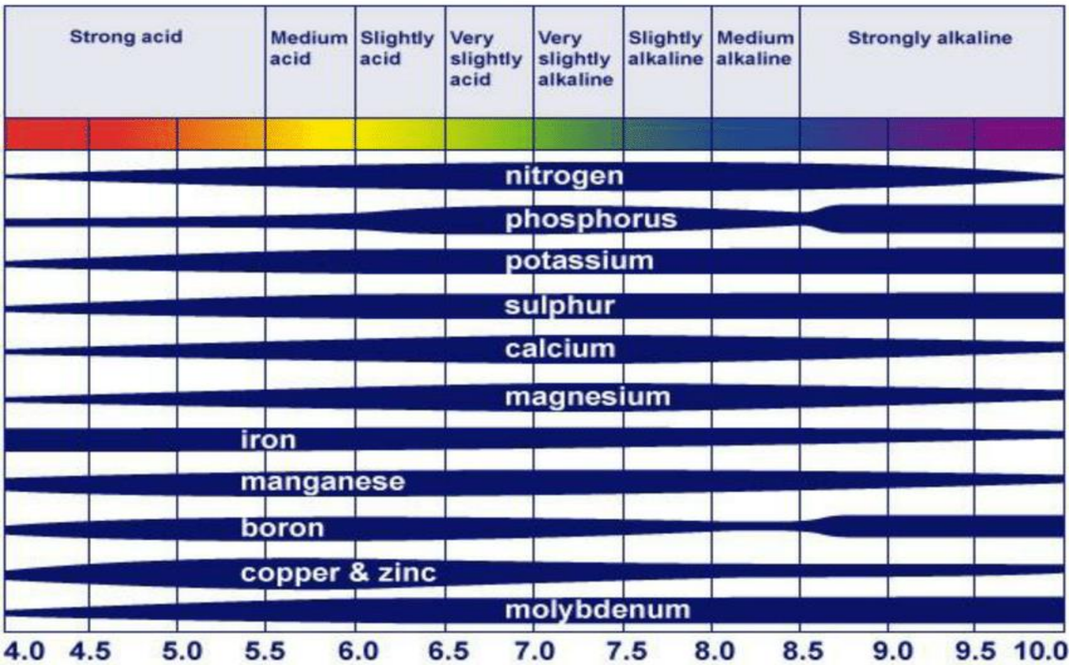


Figure 2: The effect of soil pH on nutrient availability. Source: Roques et al., 2013

2.4.2 Soil pH challenges in Kenya

Soil acidity is a major constraint on agricultural production in many parts of the world, accounting for 30% of the total land area (Kisinyo et al., 2014). In Kenya, around 13% (7.5 million hectares) of the total land area is classified as acidic (Kanyanjua et al., 2002), with the majority of this land being concentrated in western Kenya. Several studies have been done to quantify the effect of acid soils on crop yields (Osundwa, 2013; Omollo et al., 2016; Opala, 2017; Bakari et al., 2020) and the results indicated a rise in yields with the application of lime. For example, results obtained by Opala (2017) suggested that the greatest maize yield is achieved when a combination of lime and phosphorus fertilizer is applied. Other methods of increasing soil pH include manure and biochar, however, lime has shown to be the most effective amendment to neutralize soils (Hijbeek et al., 2021).

Despite the effectiveness of lime, only 3% of smallholder farmers in western Kenya use lime (One Acre Fund, 2015; Kenya Market Trust, 2019). This is due to high initial costs as well as the substantial logistics required to transport large quantities of lime to remote rural areas (One Acre Fund, 2015). These factors play a huge role in determining whether a farmer will adapt to acidification of soils through liming, rather than the lack of knowledge of the issue. A study done in counties in western Kenya showed that despite many farmers acknowledging that low yields from their farms were a contribution of acidity, few were willing to incur the expense of liming (Kenya Market Trust, 2019). In recent years, initiatives by the government and NGO's aim to encourage smallholder farmers to utilize agricultural lime, through a more sustainable supply chain involving lime manufacturers, agro-dealers, soil testing service providers and other stakeholders.

2.5 Orphan crops and their integration into food systems

The Green revolution came as a hope to achieve the ambitious Sustainable Development Goals (SDG's) of 'zero hunger' and 'good health and well-being' (United Nations, 2015) through increasing agricultural production of major crops such as maize, wheat or rice. However, this leads to monoculture as well as decreased dietary diversity (Hendre et al., 2018). This has created an over-reliance on maize within the majority of African countries. The global food system is saturated with an ever-narrowing of calorie-rich but also nutritionally limited crops (Khoury et al, 2014; Dawson et al., 2018). A viable solution to improve the state of food security within Africa must go beyond calorie sufficient meals and field-based productivity measures (Hendre et al., 2018). This was recognised by the African Orphan Crops Consortium (AOCC), which was established in 2011 and called for the re-establishment of traditional food crops (AOCC, 2018; Tadele, 2019; Dawson et al., 2018; Hendre et al., 2018). These traditional crops are often referred to as 'orphan crops' or 'underutilized crops' due to their relative negligence relative to major crops within science and development (Tadele, 2019) and are also not widely traded within international markets (Naylor et al., 2004). The AOCC has labelled 101 species of crops in Africa as orphans. All belong to major groups of crops, including cereals (e.g fonio, millet, tef), legumes (e.g cowpea, Bambara groundnut, green grams), fruits(e.g African plum, custard apple) and root and tuber crops (e.g yam, cassava) (Tadele, 2019). On average, wheat, rice, maize and sorghum each occupy 70 million ha globally per year, collectively being cultivated on 580 million ha in comparison to orphan crops occupying up to 38 million ha globally (Naylor, 2004).

Orphan crops are usually cultivated in marginal environments where the climate is harsh and soil quality is poor since these indigenous crops have been able to attain adaptive qualities to abiotic stresses such as drought, waterlogging, heat, soil acidity, soil salinity and cold and frost (Tabele, 2019; Chivenge et al., 2015, Yogeesh et al., 2016, Dawson et al., 2018). For example, finger millet has the ability for osmotic adjustment which allows the plant to maintain water potential during water stresses (Ajithkumar & Panneerselvam, 2014). Furthermore, after a flood, when the soil is waterlogged and the plants have a low supply of oxygen, millet varieties change from aerobic to anaerobic metabolism (Kulkarni & Chavan, 2013). Many orphan crops also have the capability to sustain plant growth at higher temperatures through heat-tolerant strategies which include heat shock proteins, ion transporters, signalling molecules and antioxidants (Tabele, 2019). Maize has a threshold of up to 27°C after which crop yields begin to reduce substantially (Tabele, 2019), while green gram varieties sustain well between temperatures of 28 and 30°C and 650mm of rainfall annually (Yogeesh et al., 2016). For the reasons mentioned, these neglected crops offer a viable solution to food insecurity under conditions of the rapid warming of the earth's atmosphere (Chivenge et al., 2015).

Integrating orphan crops within food systems diversifies nutrient intake as well as reduces the stress on major crops as a staple food. Orphan crops have several nutrient benefits. For instance, millets contain amino acids namely methionine, leucine, tryptophan and phenylalanine (Dawson et al., 2018; Tadele, 2009). These essential amino acids can only be obtained through the foods eaten and are vital in tissue growth, muscle rejuvenation, maintaining nitrogen balance within the body and enzyme production (Kubala, 2018). Finger millet is also a popular food amongst diabetic patients due to its low glycaemic index and slow digestion (Chandrashekar, 2010) and has anti-cancer properties (Tabele, 2019).

A more diverse cropping system that incorporates major crops with orphan crops not only allows for the attainment of food and nutritional security but is also fundamental in achieving sustainable agricultural production, regulating ecosystem and nitrogen cycles as well as maintaining biodiversity in agriculture (Chivenge et al, 2015). A study done in Nandi and Keiyo communities in Kenya shows the ability of indigenous practices to sustain food security within households (Songok et al., 2011). It was recognised that coupling indigenous knowledge systems with scientific strategies for climate change adaptation has a greater capacity for food security risk reduction (UNEP, 2008; Briggs, 2005). These integrated systems tend to be beneficial and cost-effective.

2.6 Crop modelling

Traditionally, agronomic research was primarily based on field experiments, which are a reliable source of information for understanding causal relationships between agricultural land management and observed measurements. However, these trials are usually time-consuming, labour intensive and expensive (Kephe, Ayisi & Petja, 2021) and the output of such experiments often lack sufficient data in space and time to identify appropriate and effective management practices (Jones et al, 2017). Due to these shortcomings, there was a need for the development of methods and tools to obtain results that can be made available to end-users more rapidly to aid decision-making processes. With the help of field trials, crop models were developed to meet the growing demands for data to guide policies and decisions (Rötter et al, 2011; Kephe, Ayisi & Petja, 2021).

A crop model can be defined as a collection of mathematical equations translated from the knowledge of various processes occurring within the plant and the interactions between the plant and its environment (Kephe, Ayisi & Petja, 2021; Choudhary, 2018). Crop models offer the potential to increase our understanding of the basic plant, soil and atmospheric interactions as crop and environmental sciences evolve inside computational technologies (Singels et al, 2010). They take into account the crop's biophysical processes in order to model crop growth under the effect of external factors such as crop management, climate and soil. The purpose of a crop model is to aid in explaining, understanding or improving the performance of a system and have been found to be essential for estimating future impacts of climate change on crops (Kephe, Ayisi & Petja, 2021). A wide range of crop models exists, however, utilize different approaches and levels of complexity (Wallach, 2006; Dourado-Neto, 1998; Choudhary, 2018). One such approach is a crop suitability model.

2.6.1 Empirical versus process-based crop models

There are two main types of crop modelling approaches to study the impact of climate change on crop- process-based and empirical models. As mentioned above, the Ecocrop model is an empirical model, which is developed based on using observed climate and yield data to generate future projections using simple regressions (Lobell & Burke, 2010; Kephe, Ayisi & Petja, 2021). Empirical models are frequently applied to assess agricultural climate impacts. These models have an advantage over process-based models since they can be applied to fit crop response functions based on available data, despite data being scarce or only available in an aggregated form, such as monthly climate data (Kephe, Ayisi & Petja, 2021). Furthermore, the input data which is often observational data can take into account farmers management behaviour even though it may not be implicitly observed (Roberts et al., 2017). However, acknowledging the downfalls of any crop model, empirical models solely base future projections on past conditions. This method does not provide accountability for the biological and physiological interactions between crops and variables such as climate, soil properties or pests and diseases.

In contrast, process-based models focus on simulating detailed biological and physical processes that are context-specific to a certain location (Roberts et al., 2017). The outcomes of such models simulate the crop response to different environmental conditions based on computing crop dynamics created through deterministic equations and simulations of underlying processes (Roberts et al., 2017, Lobell & Asseng, 2017). Therefore, unlike empirical models, process-based models can be used to aid the decision-making process of agronomic adaptation techniques through the evidence of the interactions between crop growth and other constraining variables (Lobell & Asseng, 2017). Examples of process-based models include Decision Support System for Agro-Technology Transfer (DSSAT), Crop Environment Resource Synthesis-Maize (CERES-Maize), and Agricultural Production Systems Simulator (APSIM). However, at a large spatial scale, process-based models were found to provide inadequate information on the impacts of climate found at a farm scale, though the efforts to improve this have been taken up by the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al., 2013). Therefore, for this study, an empirical model was chosen based on its ability to calculate projections over a large spatial scale.

2.6.2 Crop suitability models

Crop suitability models are often applied to quantify the biophysical land use potential based on current and future climatic conditions at a regional scale (Piikki et al, 2017; Kephe, Ayisi & Petja, 2021). The outcomes of such a model highlight regions of decreasing or increasing suitability of a particular crop, which may suggest shifts in cultivation zones and land use types (Kephe, Ayisi & Petja, 2021). The analysis of the suitability of crop production under climate change scenarios has been made possible by the progress made in remote sensing and geographic information technology (Zhang et al, 2017). This allows for research to be conducted for areas where data collection of climatic variables is not consistent. This is a vital tool in designing alternate cropping systems adapted to future climate (Hyun et al, 2017; Piikki et al, 2017) by filling the information gaps of the suitability of underutilized or neglected crops (Ramires- Villegas et al, 2013). Diversification of cropping systems presents itself as a growing need due to climate change altering the distribution of crops globally, with decreasing suitability within tropical regions (IPCC, 2014). For instance, rainfed maize within East Africa is likely to shift from lower elevation regions to higher elevation regions, where temperatures are lower and rainfall is higher, having a substantial impact on the production of the major staple crop (Kogo, 2019). A greater emphasis on crop suitability models has been put on Kenya's agricultural sector due to the limited documentation of future projections of crops under climate change scenarios. This study uses the EcoCrop suitability model to understand the consequences that future climates have on a variety of crops in Kenya.

EcoCrop is a simple niche-based empirical model that uses a range of environmental factors, i.e. rainfall, minimum and average temperature, to produce a suitability index as an output (Ramirez-Villegas et al., 2013). These outputs range from 0:totally unsuitable to 1:excellent suitability (Hunter & Crespo, 2019). Despite the simplicity of this model, EcoCrop has shown to produce results that are similar to those of more complex models under certain conditions (Ramirez-Villegas et al., 2013) and have therefore encouraged the use of the model where extensive agronomic data is not available (Piikii et al., 2017). There are several used cases of Ecocrop within Sub-Saharan Africa, for example, Hunter and Crespo (2019) used the model to calculate anomalies in the suitability of cassava and maize in Angola. Ramirez-Villegas, Jarvis and Läderach (2013) also used Ecocrop, with sorghum as a case study, to calibrate and analyse the impacts of climate on sorghum climatic suitability. However, there is a research gap in the use of Ecocrop to study crops in Kenya, therefore, this study aims to contribute towards this.

One advantage of using Ecocrop is the good performance for predicting climatic suitability and crop distribution even when using the default parameters reported in the FAO-Ecocrop database (Jarvis et al., 2012). The performance of the Ecocrop model has been tested in past studies conducted in Africa (Jarvis et al., 2012; Piikki et al., 2017; Egbebiyi, Lennard & Crespo, 2019). For example, over West Africa, the model evaluation shows a strong spatial correlation ($r > 0.7$) (Egbebiyi, Lennard & Crespo, 2019) and a positive correlation between Ecocrop suitability values and the area in each region of Tanzania where common beans were planted (Piikki et al., 2017). This gives some level of confidence in the use of Ecocrop.

Chapter Three: Materials and Methods

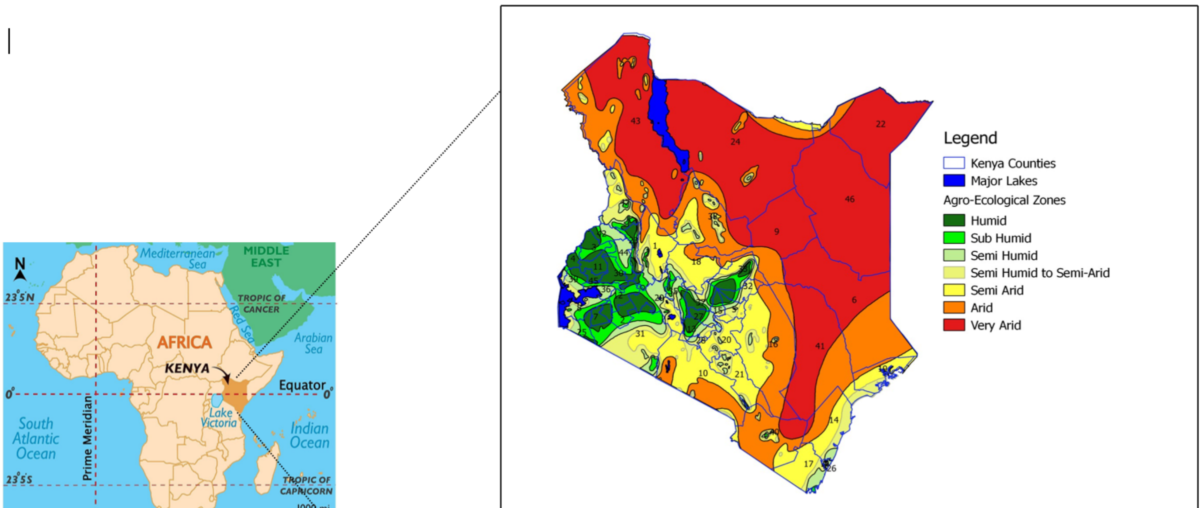
Chapter three describes the study site in terms of different agroecological zones in the country. The methods and data used for this study are also outlined. The data acquired includes CORDEX climate data and pH soil grids from SoilGrids. The chapter also provides an explanation of how Ecocrop was used to calculate suitability scores and the use of QGIS to assess the impact that soil pH has on crop suitability.

3.1 Study site

Kenya being at the equator, with a latitude ranging from 5°N to 5°S and longitude between 34°E and 42°E, does not experience great variability in temperature which ranges from 15 to 35°C. Since 1960, an average annual increase of 0.21°C has been recorded, with projections of a temperature increase of almost 2.7°C by 2060s (GoK, 2012). Rainfall in Kenya is bimodal, with long rains occurring between March to May and the less intense short rains between October and December. Kenya is characterized by 7 distinct agro-ecological zones (Figure 3) which group areas based on the combinations of soil, landform and climatic characteristics (FA0, 1996). The agro-ecological zones in Kenya include (I) humid; (II) sub-humid; (III) semi-humid; (IV) semi-humid to arid; (V) semi-arid; (VI) arid; and (VII) very arid (Kogo et al, 2019).

Zone I: Humid

This zone is concentrated in areas of higher altitudes, ranging between 1980 and 2700m above sea level (GoK, 2018), surrounding the slopes of Mt Kenya, Mt Elgon and the Mau and Aberdares mountain ranges (Sombroak, et al., 1982). This zone receives the greatest amount of rainfall within the country, with a minimum rainfall of 1000mm per year (GoK, 2018). This allows for the growth of thick vegetation and can support dense forests and open grasslands. Kakamega is one such county that is characterized within the humid region. Kakamega county has a population of 1.8 million people who support an economy mainly built through crop, livestock and dairy production. The climate ideally supports the production of sugarcane, beans, cassava tea, sorghum and maize, the latter being a staple food in the county (County Government of Kakamega county, 2015).



1 BARINGO	13 KIAMBU	25 MIGORI	37 NYERI
2 BOMET	14 KILIFI	26 MOMBASA	38 SAMBURU
3 BUNGOMA	15 KIRINYAGA	27 MURANGA	39 SIAYA
4 BUSIA	16 KITUI	28 NAIROBI	40 TAITA TAVETA
5 EMBU	17 KWALE	29 NAKURU	41 TANA RIVER
6 GARISSA	18 LAIKIPIA	30 NANDI	42 TRANS NZOIA
7 KISII	19 LAMU	31 NAROK	43 TURKANA
8 HOMA BAY	20 MACHAKOS	32 THARAKA	44 UASIN GISHU
9 ISIOLO	21 MAKUENI	33 MERU	45 VIHIGA
10 KAJIADO	22 MANDERA	34 NYAMIRA	46 WAJIR
11 KAKAMEGA	23 MARAKWET	35 NYANDARUA	47 POKOT
12 KERICHO	24 MARSABIT	36 KISUMU	

Figure 3: Map of Kenya, encompassing County boundaries and Agroecological zones. Source: GoK, Ministry of Environment and Forestry and Global atlas

Zone II: Sub-Humid

This zone contributes to a large proportion of Central Rift-Valley with an elevation of 900-1800m ASL and annual rainfall between 950 and 1500mm (GoK, 2018). These conditions provide optimum conditions for agriculture and thereby harbour a large portion of agriculture cultivation which is often integrated with dairy farming, for instance in counties such as Nakuru, Bungoma and Busia. The economy of Bungoma county is mainly agriculture centred on maize and sugarcane industries (Bungoma County Government, 2020). Busia county heavily relies on fishing and agriculture production of cassava, millet, sweet potatoes, maize and beans (Busia County Government, 2020). Both Bungoma and Busia fall within the Sio sub-catchment which houses several tributaries of the River Sio (Muli, 2019).

Zone III: Semi-Humid

The elevation of this zone is similar to that of the sub-humid zone, ranging between 900-1800m ASL, however, it receives less annual rainfall ranging from 500-950mm (GoK, 2018). This zone makes up the surroundings of Naivasha, Laikipia, Machakos counties as well as the Southern part of the coast. Kirinyaga and Meru county form part of the foothills of Mt. Kenya and are endowed with fertile soils and favourable climatic conditions to support their primarily agrarian economies. In Meru County, the production of a variety of commodities including wheat, barley, potatoes, millet, sorghum and maize, high-grade tea, coffee, bananas are grown within the county (Meru County Government, 2017). Kirinyaga County is well known for its rice production, as well as other crops such as maize, beans, tomatoes and other horticultural crops.

Zone IV: Semi-Humid to Semi-Arid

The semi-humid to semi-arid zone makes up a large part of coastal provinces, with low elevation. Rainfall ranges between 200-400mm annually and tends to be very erratic (GoK, 2018). The agriculture sector plays a crucial role in creating employment, ensuring food and nutrition security and reducing poverty within these counties, with an average of 10.6% of the county's total area being designated to agriculture activities (MoALF, 2016). The main crops grown within the zone include maize, beans, green grams while commercial crops grown include cashew nuts, coconuts and sugarcane (Kwale County Government, 2019).

Zones V, VI and VII: Arid and Semi-Arid zones

The Arid and Semi-arid zones constitute around 80% (467,200 km^2) of Kenya's total landmass, covering the majority of North and Southeastern parts, Northern Rift Valley and Coastal regions (Mwenda et al., 2016). These zones house around 35% of Kenya's population and receive 200-400mm of rainfall within a year, with some regions being classified as desert land, represented by the Chalbi desert in Marsabit. Typical vegetation in this zone is bushland and scrubland as a result of high daytime temperatures (FAO, 2001). However, in recent years, growing crops such as roots and tubers have emerged (Daily Nation, 2018). Taita Taveta, Tana River, Kitui, Machakos and Kilifi are examples of counties that are characterised as very arid to semi-arid. Counties in this region have population densities ranging from 14 to 117 persons per km^2 (KNBS, 2019), whereby small scale agriculture and nomadic pastoralism serve as the backbone of the economy due to dry conditions and erratic rainfall.

3.2 Data

3.2.1 Climate data

For this study, three climate variables were used to determine crop suitability- rainfall, minimum and maximum temperatures. Temperature and rainfall are key indicators of climate change as well as key inputs in agricultural production (Egbebiyi, Crespo & Lennard, 2019; Cong & Brandy, 2012). Rainfall has the potential to affect plant production in terms of leaf area and photosynthesis productivity (Cantelaube & Terres, 2005; Olesen & Bindi, 2002), while temperature contributes to determining the length of a growing season and seed production (Lobell & Asner, 2007). Ecocrop is a favourable model since it is able to encapsulate the interdependence between temperature and rainfall.

Modelled climate data for historical (1980-2015), early century (2010-2039) and mid-century (2040-2069) was obtained from the Coordinated Regional Downscaling Experiment (CORDEX- http://www.csag.uct.ac.za/cordex-africa/). CORDEX was developed by the World Climate Research Program (WCRP) to evaluate and advance the methods of downscaling Global Climate Model (GCM) projections to produce regional climate information (Omar, 2014).

GCM's are complex mathematical representations of major climate system components- the atmosphere, land surface, oceans and sea ice. Understanding the interactions between these components allows for climate projections on a global scale (NOAA, 2020). Downscaling of global climate data is a procedure that takes large scale information to make predictions at a local scale to produce higher resolution climate data. The process of downscaling climate information involves two methods: dynamic and statistical downscaling. Dynamical downscaling requires running high-resolution climate models on regional domains while using observational data or a lower-resolution climate model as boundary conditions (Hoar & Nychka, 2008). Statistical downscaling involves the process of associating local climate variables and large-scale predictors to the output of global climate models experiments to produce local climate conditions (Hoar & Nychka, 2008). CORDEX includes both downscaling models, with both methods resulting in higher resolution regional climate information. A study that modelled green gram production in Kenya assessed the performance of the ability of CORDEX to simulate past climate and came to a conclusion the model overestimated rainfall over Mt Kenya and Mt Kilimanjaro regions, however, the overall CORDEX model performance was better than individual climate models. This was especially true for simulated temperatures (Mugo, 2018). For this study, data from 4 CMIP5 GCMs (Table 2), downscaled by the Regional Climate Model (RCM) SMI-RCA4, was used as an input for the Ecocrop model under RCP8.5 and RCP4.5 scenarios.

Table 2: List of dynamically downscaled GCMs used for this study

Model Name	Modelling Institution	Resolution
ICHEC	EC- Earth consortium	1.25° x 1.25°
HadGEM2-ES	UK Met Office Hadley Centre	1.9° x 1.3°
MPI-ESM-LR	Max Planck Institute for meteorology	1.9° x 1.9°
GFDL_ESM2M	NOAA geophysical fluid dynamic laboratory	2.5° x 2.0°

The selection of the GCMs used was based on their ability to accurately capture atmospheric teleconnections. This forms a vital basis for the usefulness and evaluation of climate change projections. RCMs driven by MPI-ESM-LR, ICHEC, HadGEM2-ES and GFDL_ESM2M were found to perform better than other GCM's in predicting Sea Surface Temperature (SST) and rainfall patterns such as El Nino, La Nina and the IOD phenomena's over East Africa (Endris et al, 2016).

3.2.3 Soil pH

Soil pH (H_2O solution) predictions for this study was downloaded from SoilGrids250, released in May 2020 (https://soilgrids.org/). SoilGrids250 depicts a high-resolution dataset that has interpolated soil sample properties using a wide range of remotely senses environmental covariates, such as elevation and its derivatives (e.g slope), landforms, climatic variables and lithology maps (Hengl et al., 2017; Cramer et al., 2019). These covariates are associated with soil data using machine learning algorithms to map out predictions of physical and chemical soil properties such as soil pH, bulk density, cation exchange capacity, total nitrogen and organic carbon. Of all 15 soil covariates targeted for soil pH, precipitation and surface reflectance are the primary influences. Soil pH was observed to have a linear relationship with total annual rainfall (Cramer et al., 2019).

In addition to the dominance that pH has on the growth of crops in Kenya, soil pH was chosen as a variable for this study due to the ability of SoilGrids to project this soil property. Previous tests to determine this were done through the ranger package which reports model fitting success through the R-squared based on Out-of-Bag (OOB) sample. The results indicated the highest variation explained by the model of 0.85 (85%) for soil pH (Kengl et al., 2017).

The pH in Kenya ranges from 4 (acidic) to 10 (alkaline), with more acidic sails being concentrated in the humid and sub-humid zone of the country (Figure 4). Western Kenyan soils, in counties such as Bungoma, Busia, Kakamega, Vihiga and Central Kenya, such as Kirinyaga and Embu are characteristically acidic (<pH 7). This is an attribute of the high rainfall in the region which increases soil moisture which leads to proton generation associated with nitrification (Zárate-Valdez et al, 2006). This is also seen along the coast, where humidity is high. In contrast, denitrification occurs when the soil is below saturation and results in an increase in pH. This explains the alkaline soils (>pH 7) in arid and semi-arid zones of Kenya, such as Wajir and Isiolo. Marsabit and Turkana have the highest range of soil pH, which can be explained by the irrigation water which is taken from Lake Turkana, for instance, the Todonyang irrigation scheme (Avery & Tebbs, 2018). This water body is the largest alkaline lake in the world, with a pH between 9.2 and 9.4.

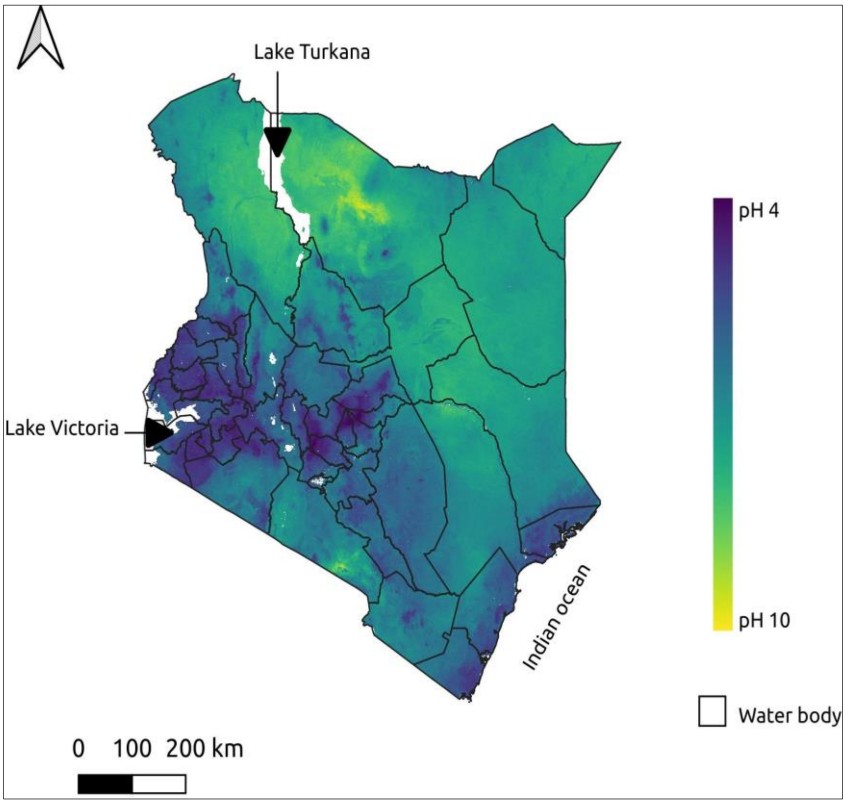


Figure 4: Soil pH predictions for Kenya. The colour scale represents the pH scale

3.3 Methodology

3.3.1 Ecocrop model description

The suitability of crops under future climate projections was done using the Ecocrop suitability model. It was initially developed by Hijmans et al (2001) as part of DIVA-GIS and was later incorporated into the Food and Agriculture Organisation- Ecocrop database thereby being named EcoCrop (Ramirez-Villegas et al., 2013).

The model is a basic empirical model built on two ecological ranges defined by variables of temperature and rainfall which are defined by a pair of parameters. The first is the absolute range which outlines the minimum and maximum temperatures at which a crop can grow, defined by T_{MIN-C} and T_{MAX-C}, as well as the minimum and maximum rainfall that the crop requires, defined by R_{MIN-C} and R_{MAX-C}. Anywhere outside this range returns as an unsuitable score for the variable (0). Second is the optimum range which is defined by the minimum optimum and maximum optimum temperature annotated by $T_{OPMIN-C}$ and $T_{OPMAX-C}$, minimum optimum and maximum optimum rainfall annotated $R_{OPMIN-C}$ and $R_{OPMAX-C}$ (Figure 5). Anywhere inside this range returns a perfect suitability score for the variable (1) (Hijmans et al., 2013; Ramirez-Villegas et al., 2013). An additional parameter, T_{KILL}, is used to illustrate the temperature at which a given crop can no longer survive (Ramirez-Villegas et al., 2013).

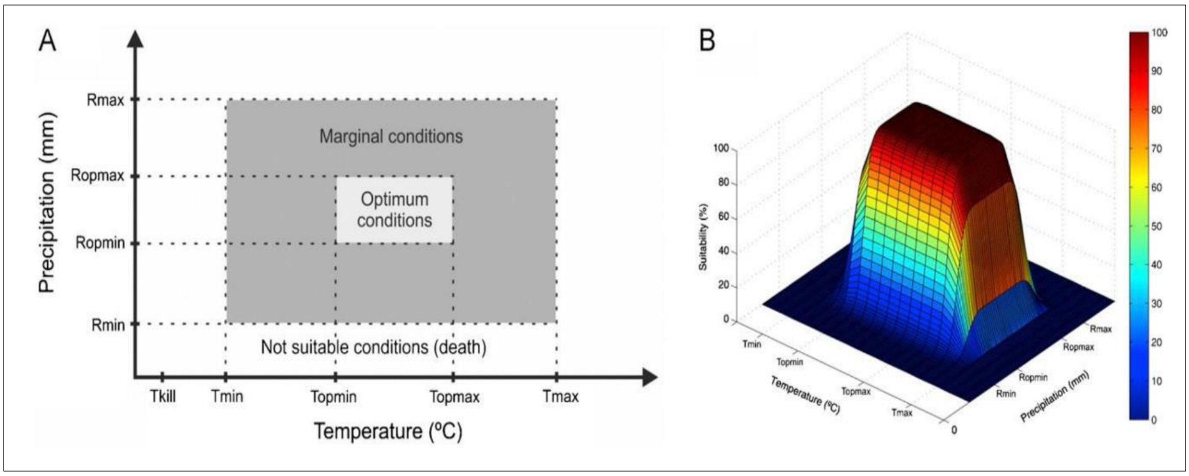


Figure 5: Two dimensional and (B) three-dimensional illustration of the two ecological ranges within Ecocrop. Source: Ramirez-Villegas et al., 2013

The model calculates temperature (T_{SUIT}) and rainfall (R_{SUIT}) suitability separately, after which they are multiplied to calculate their interaction. Ecocrop first requires the duration of the growing season to be defined. For any given site, for each month of the growing season and for each of the 12 possible growing seasons of the year, the temperature suitability (T_{SUIT}) is calculated. T_{SUIT} is calculated by comparing the crop parameters (table 3) with the climate data. Unlike temperature suitability, rainfall suitability is only calculated once, through the total cumulative rainfall over the growing season of the crop, rather than rainfall for each month. The final rainfall suitability is the maximum value for all the growing seasons.

The final suitability score is calculated by multiplying T_{SUIT} and R_{SUIT}. Suitability scores are grouped by very marginal (1-20%), marginal (20-40%), suitable (40-60%), very suitable (60-80%) and excellent (80-100%). When conditions are beyond absolute thresholds of rainfall and temperature, the suitability score is zero and falls within the white area of Figure 5A. When conditions range between absolute and optimum a suitability score from 1 to 99 is given (dark grey area- Figure 5A) and when variables are under optimum conditions the suitability score is 100, falling within the light grey area in Figure 5A. Suitability scores indicate the most favourable month for planting.

This study assessed the change in suitability of five crops; maize, finger millet, common bean, broad bean and sweet potato; rather than the absolute values of suitability for future periods. For this reason, model performance was not tested in this study.

3.3.2 Ecocrop thresholds for suitability

Temperature and rainfall thresholds used to calculate suitability were obtained from the FAO Ecocrop database, which is built on extensive literature and expert views on these crops (Ramirez-Villegas et al., 2013; Egbebiyi, Crespo & Lennard, 2019; Chapman et al., 2020). This database was extracted using the "R-dimso" package on the cran R software (Hijmans et al., 2017) (https://cran.rproject.org/web/packages/dismo/index.html). Although thresholds may vary depending on different crop varieties, soil properties, altitude or climate, the Ecocrop database is able to provide a general validation of the thresholds which makes a useful tool for assessing climate change and its impact on crop suitability over large areas (Egbebiyi, Crespo & Lennard, 2019). The set thresholds also make for a good reference point to compare to other crop suitability studies. Table 3 provides information on the crop thresholds in terms of absolute and optimum rainfall and temperature for maize, finger millet, green grams, common bean and sweet potato.

Table 3 Crop thresholds set within the Ecocrop database

Crop	Scientific name	Growing duration (days)	Temperature (°C)				Rainfall (mm)			
			T_{MIN}	T_{OPMIN}	T_{OPMAX}	T_{MAX}	R_{MIN}	R_{OPMIN}	R_{OPMAX}	R_{MAX}
Maize	*Zea mays*	65 – 365	10	18	35	47	400	600	1200	1800
Finger millet	*Eleusine coracana*	75 - 180	8	18	27	35	600	800	1100	4300
Broad bean	*Vicia faba*	100 - 150	5	18	28	32	250	650	1000	2600
Common bean	*Phaseolus vulgaris*	50 - 270	7	16	25	32	300	500	2000	4300
Sweet potato	*Ipomoea batatas*	80 - 170	10	18	28	38	500	750	1750	5000

3.3.4 QGIS raster calculations and pH thresholds

Soil pH (in water) data were downloaded from SoilGrids250 and processed in QGIS version 3.16.3-Hannover. QGIS is an Open Source Geographical System that was first released in May 2002 and is developed using the Qt toolkit and C++ (Gracer, 2013). Raster layers were merged for the data tiles for each area and resampling of the data was done with GRASS'S r.resamp.stats command. Resampling was done to match the resolution of the Ecocrop outputs, which was based on the climate resolution from CORDEX. The command resamples raster map layers to a coarser grid by aggregating the values of all input cells whose centres lie within the output cell or which intersect the output cell (GRASS Development Team, 2014). Thereafter, using the raster calculator, maps were created where suitable pH for each crop overlapped climate suitability generated by the Ecocrop model. Two ranges were created to assess the level of ph and climate suitability: 1) where a wider soil pH range and climate suitability greater than zero spatially overlap, 2) where pH range is optimum and climate suitability is greater than 40% (suitable conditions). Unsuitable conditons are those when climate suitability is zero and the pH threshold is beyond that of the plants' threshold.

The pH range for each crop was determined through literature to find the most common recommendation for pH. Maize grows most effectively with the soil pH range of 5.5 to 7.3, with the optimum range between pH of 6 to 6.5 (Kanyanjua, 2002). Within this range nutrients such as nitrogen, potassium, magnesium and phosphorus are readily available for the growth of maize crops. It is important to acknowledge that different seed varieties could have different pH requirements within this range. For instance, the local cultivar Githigu, commonly found in central Kenya have adapted to growing within the lower end of the tolerance range (Kanyanjua, 2002). In contrast, finger millet can be grown in a wide range of soils, allowing for a broader pH range of 5 to 8, as long as the soil is fertile, well-drained and a sandy loam texture. The optimum range is similar to that of maize, with a pH between 6 and 6.5.

The pH tolerance range of common beans is between pH 5 and 7.5. In very acidic soils (pH < 4.5), plant growth is threatened by the limited development of the Rhizobium bacteria that are responsible for nitrogen fixation. Nitrogen fixation is a chemical process by which atmospheric nitrogen is transferred into the soil. The role that Rhizobium bacteria plays is the association with legume crops such that the bacteria attaches onto the root of the crop to produce nodules, which allows for the transfer of nitrogen (Jensen et al., 2010). Nitrogen is essential for the growth of several crops and therefore intercropping or rotation with such legume crops is highly encouraged. However, this can not be possible in very acidic soils unless artificial Rhizobium inoculants are applied, or the soil pH is alternated through liming practices. Both these options tend to be very expensive for smallholder farmers. Broad beans follow the same trend and can not grow in acid soils, with a pH tolerance range of 6.5 to 9 (Jensen et al., 2010; Tadele, 2020).

In comparison to the other crops used for this study, sweet potato can grow in the most acidic soils, as low as pH4. This is due to soil acidity tolerance as well as aluminium. In soil with a pH of less than 5, aluminium becomes soluble and phototoxic-aluminium ($Al3+$) affects the ability of a plant to absorb moisture and nutrients. However, sweet potato is considered to be moderately tolerant to aluminium.

Table 4: Summary of pH tolerance ranges and optimum pH range of maize, finger millet, common bean, broad bean and sweet potato
Source: Kanyanjua, 2002; Kanyanjua, 2002; Jensen et al., 2010; Tadele, 2020

Crop	pH Tolerance range	Optimum pH range
Maize	5.5 to 7.3	6 to 6.5
Finger millet	5 to 8	6 to 6.5
Common bean	5 to 7.5	6.5 to 7
Broad bean	6.5 to 9	7 to 8
Sweet potato	4 to 6.5	5.5 to 6.5

Chapter Four: Results

4.1 Climate change

4.1.2 Mean and minimum temperature

The monthly mean (Appendix 1 and 2) and minimum temperature (Figure 6 and 7) followed similar patterns both spatially and temporally. Historical temperatures support the same message as the agroecological zones (Figure 3), with central Kenya having lower temperatures throughout the year, compared to the arid regions in the north and northeast of the country. It can also be noticed that there is a greater seasonal change in temperature in warmer counties such as Taita Taveta, Wajir and Turkana, where, for instance, the hottest months are between March to June, which coincides with the long rains, while July to September presents relatively cold average and minimum temperatures. In comparison, humid and sub-humid zones of central Kenya have average temperatures of around 15°C throughout the year.

Under RCP 8.5 conditions for minimum and average temperature (Figure 6 and Appendix 1, respectively), the near-term (2010-2039) temperatures are predicted to increase by an average of 1°C, with July and December having a more prominent increase of 1.5°C and is widespread throughout the country. Counties in western Kenya, such as Turkana, Uasin Giushu and Trans Nzoia are predicted to experience a greater rise in temperature, of about 1.5°C throughout the year. The trend of rising temperatures is also predicted for the mid-century period, with the majority of the country predicted to experience a 2°C - 2.5°C rise in temperature. During the long rain season, higher temperature increases are seen in the north and north-eastern parts of the country, while during the short rain season, a greater rise in temperature is foreseen in western and central areas.

RCP 4.5 climate conditions are met with rising minimum and average temperatures (Figure 7 and Appendix 2, respectively) of around 0.5°C during the near term. This is the case in the majority of the counties, however, during the dry season between July and September, counties in northwest Kenya such as Turkana, Siaya and Busia are set to experience a 1°C rise in temperature. During the mid-century, the majority of the counties throughout the year are predicted to experience a temperature increase of around 1.5°C, apart from the months between May and September, whereby a 2°C is projected.

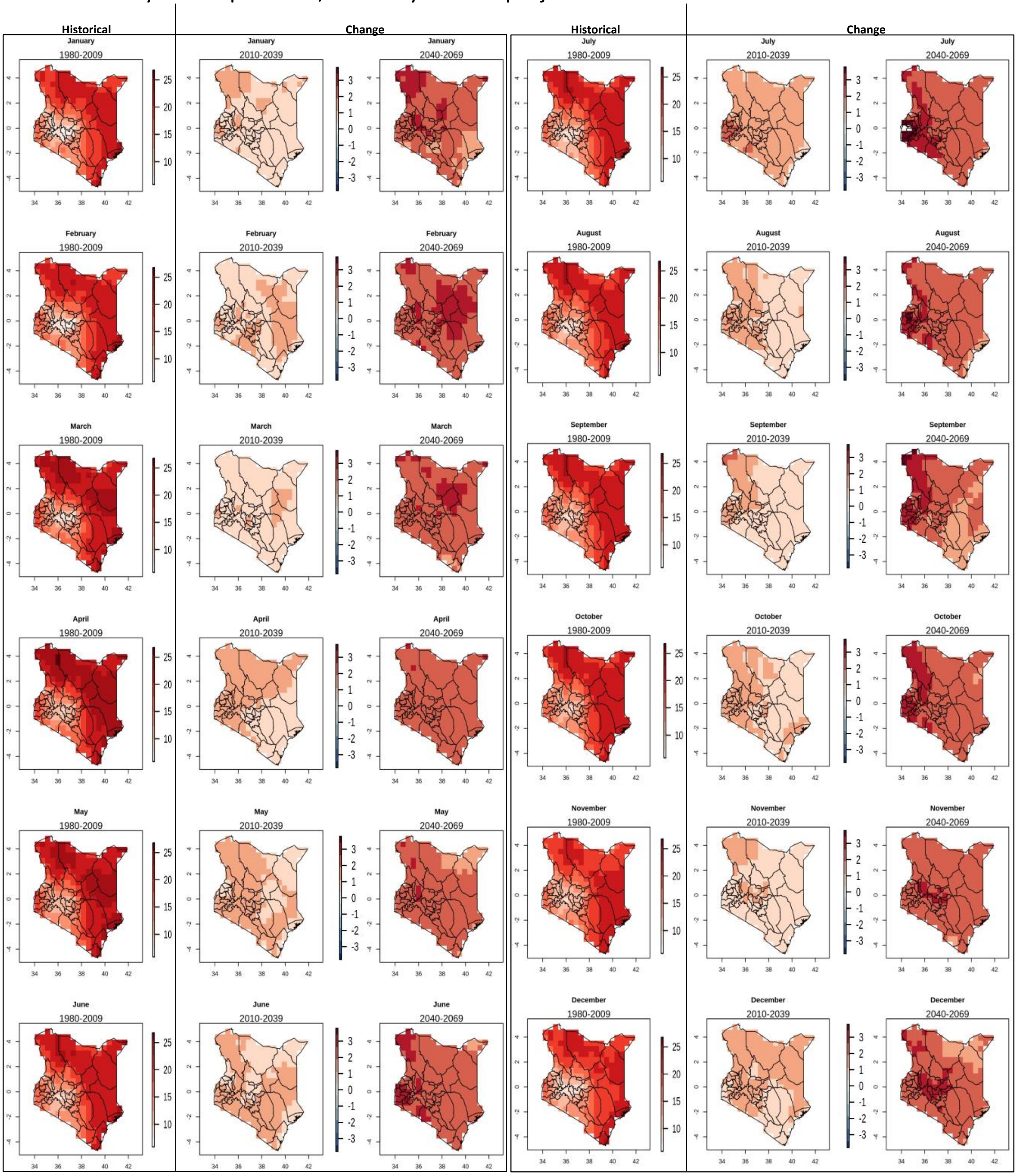


Figure 6: Historical (column 1) and projected changes (column 2 and 3) in minimum temperature (TASMIN) over Kenya for the near term (2010-2039) and mid-century (2040-2069) under the RCP8.5 pathway

The overall difference between RCP8.5 and RCP4.5 is most profound during the mid-century period. Under RCP8.5 temperatures are predicted to rise one degree more than that of under RCP4.5 conditions. For instance, in September, regions that are predicted to have a 1.5°C and

2.5°C during RCP4.5 will experience a 2°C-2.5°C and 3°C rises under the RCP8.5 pathway. Under both pathways, in both future periods, eastern Kenya is seen to have the greatest degree of temperature rise compared to the rest of the country.

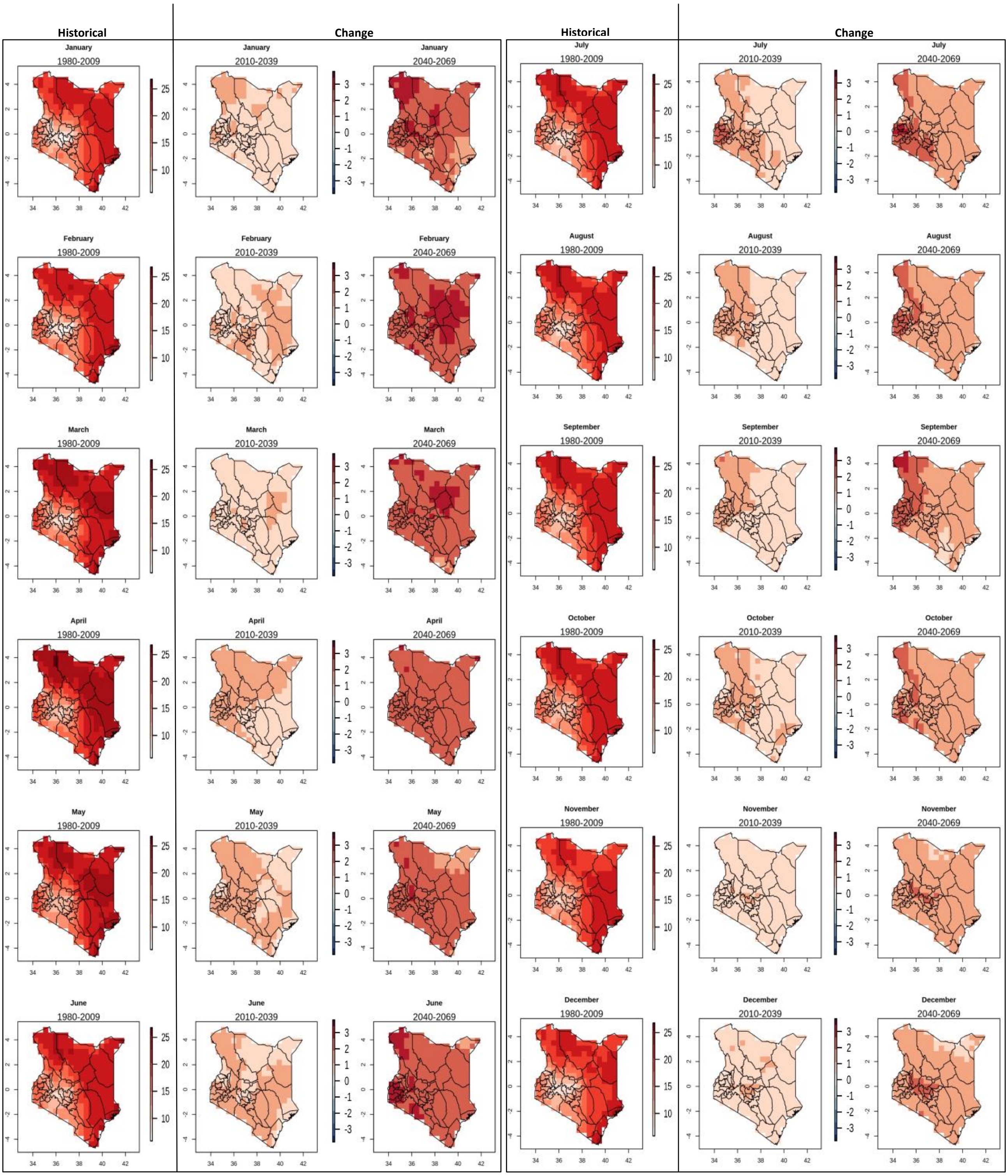


Figure 7: Historical (column 1) and projected changes (column 2 and 3) in minimum temperature (TASMIN) over Kenya for the near term (2010-2039) and mid-century (2040-2069) under the RCP4.5 pathway

4.1.3 Rainfall

Historical rainfall patterns clearly show distinguished dry and wet seasons, with the onset of the long rains in March and October for the short rains. Between March and June, a significant amount of rainfall is experienced in Central Kenya, within humid and semi-humid regions of the slopes of Mt Kenya, with rainfall ranging between 800 and 1200m. The eastern and northern parts of the country also experience this seasonal rainfall, with May being the peak. The short rains between October and December show a greater spatial variation in comparison to the long rains. This is seen within the arid regions in eastern Kenya which received around 400mm in October and November, compared to 200mm in April and May within the majority of this region. During the dry season, the majority of the country receives 200mm or less of monthly rainfall.

Under the RCP8.5 pathway (Figure 8), in the near future, there is a prominent increase in the amount of rainfall experienced in March and April, as well as an increase in the spread of rainfall throughout the country. In April, rainfall is largely increasing by around 50-100mm in arid regions of eastern Kenya. However, a decrease in May is projected in western Kenya. This may suggest in the latter that the long rains could become more intense over a shorter period. The dry season between June and August is showing a decrease in rainfall in the western regions of Kenya, such as in Bungoma, Busia and Turkana. During the mid-century, the decreased rainfall between May and August is intensifying, with regions set to experience a 200mm decrease in rainfall. During October and November, there are significant increases in monthly rainfall which are widespread within the country. For instance, the 400mm historical precipitation in November in arid counties, could reach by the mid-century, the minimum threshold for growing crops such as green grams with just a 100mm increase.

In comparison, the RCP4.5 climate pathway (Figure 9) leads to very minimal change in rainfall in March and April for both future periods, however, very similar changes to RCP8.5 occur in May with a decrease in monthly rainfall between May and August. During September within the mid-century period, rainfall is predicted to increase by an average of 100mm in the north and north-western counties of Kenya. This may have an impact on the timing of planting since the onset of the short rains would start sooner than October. Rainfall is also predicted to increase in October and November in the mid-2040-2069 period. The difference in the changes between the long and short rains could result from large scale climatological drivers, for example, the Indian Ocean Dipole is said to have a greater contributing factor to the short rains in Kenya (Conway et al., 2007; Ogwang et al., 2018; Owiti et al., 2008)

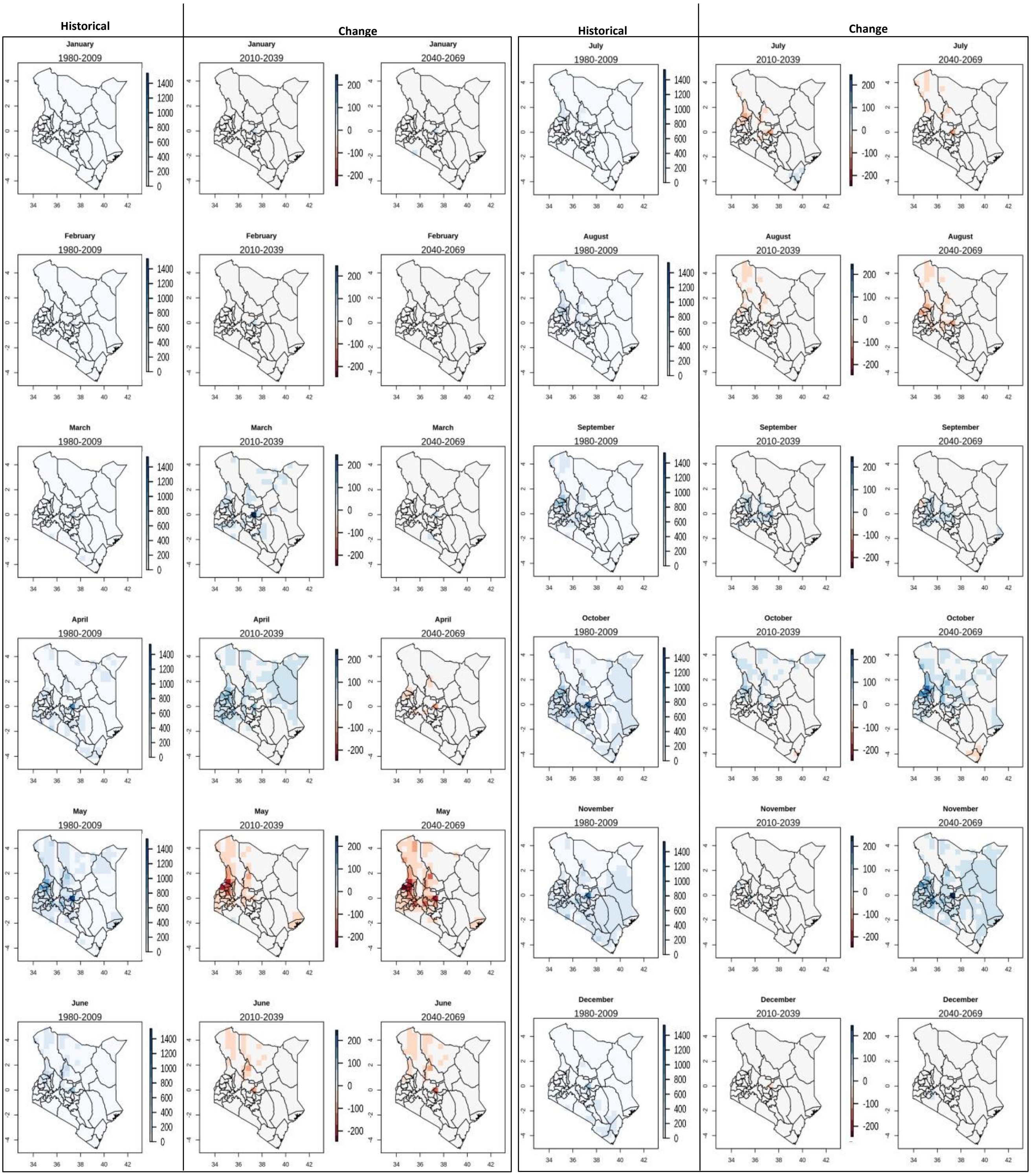


Figure 8: Historical (column 1) and projected changes (column 2 and 3) in precipitation (PREC) over Kenya for the near term (2010-2039) and mid-century (2040-2069) under the RCP8.5 pathway

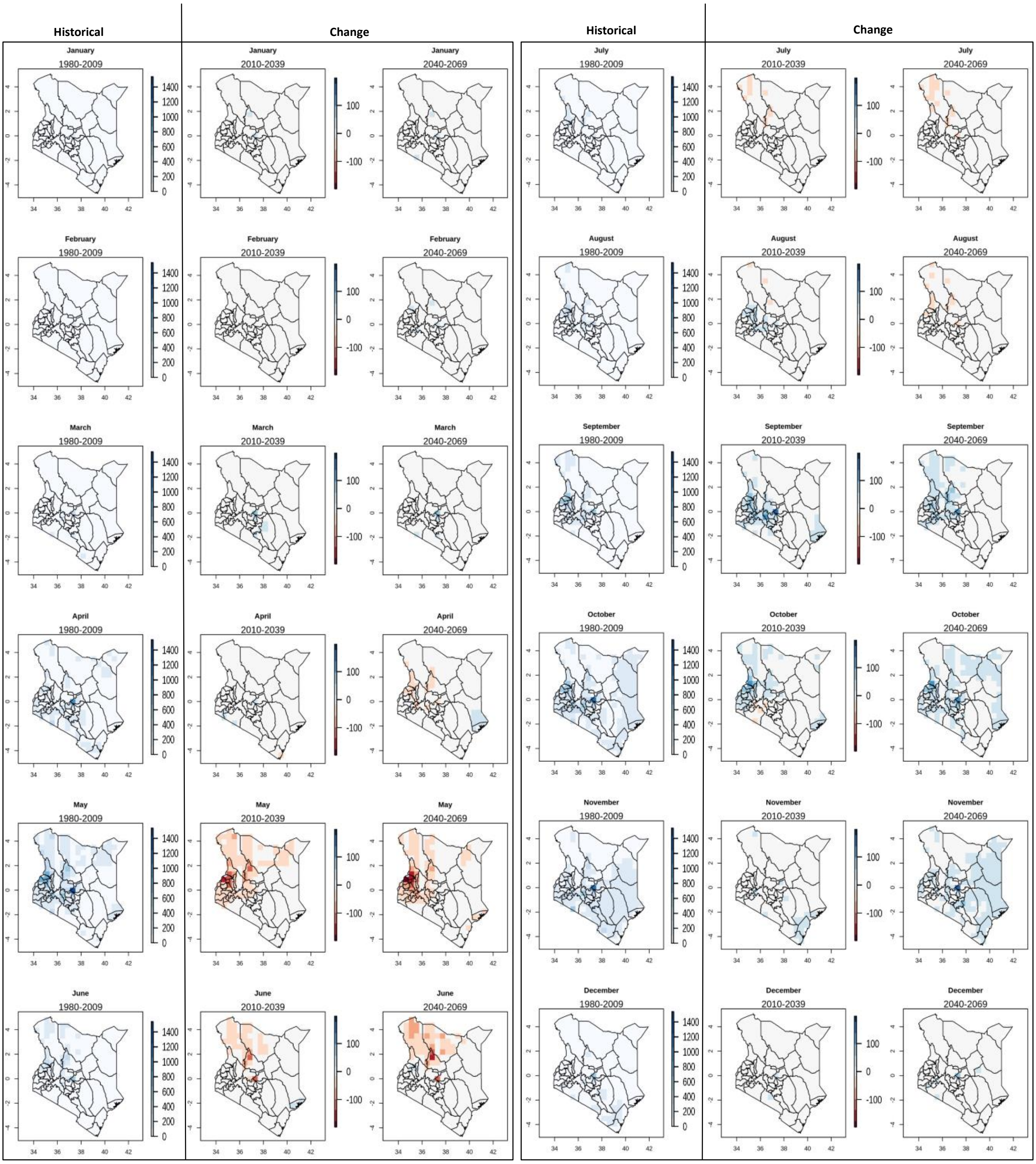


Figure 9: Historical (column 1) and projected changes (column 2 and 3) in precipitation (PREC) over Kenya for the near term (2010-2039) and mid-century (2040-2069) under the RCP4.5 pathway

4.2 Ecocrop suitability scores

4.2.1 Change in suitability under RCP8.5 climate conditions

The Ecocrop model was used to simulate crop suitability for cereals (maize and finger millet), legumes (common bean and green grams) and a root (sweet potato) with the CORDEX RCP8.5 climate inputs. The spatial suitability representation under historical climates (1980-2009) indicates low or no suitability of crops amongst counties in north-eastern Kenya. This is attributed to the arid conditions of the region whereby rainfall is seen to be sparsely distributed throughout the long rains (March to May) and temperatures that exceed the maximum range at which the crops can grow. However, historically, the consensus of all seven crops studied was the marginal to high suitability in Eastern and Central Kenya, which are characterized by humid, sub-humid and semi-humid zones. Historically these counties have indeed been the breadbasket for the country.

4.2.1.1 Cereals crops

The change in crop suitability between historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) for maize and finger millet during the long rains (March to June) and short rains (October to December) is presented in figures 10 and 11, respectively. In Kenya, maize and millets are grown in both rainy seasons. Historically, maize experiences a larger suitability area and higher Suitability Index Values (SIV) in comparison to finger millet. This is evident as more counties in central, western and along the coast present suitable conditions to grow maize and not finger millet, for example in Baringo, Muranga, Kilifi and Kwale. Maize is seen to have suitable to excellent conditions in the majority of the counties that are classified as humid, sub-humid, semi-humid and semi-arid. The suitability of finger millet has been very scattered in both the long and short rains, the latter being especially true, with the majority of SIV's 30% or below. Both crops are unsuitable in arid counties such as Wajir, Mandera and Marsabit.

During the long rains, within the near term period, the SIV of maize along the coast is seen to decrease by almost 0.2 (20%) with no other significant changes within the rest of the country. Within the same region, the suitability of growing finger millet is seen to significantly increase progressively from near term to mid-century, with a rise in SIV of around 0.5 (50%) in a region that previously had zero suitability for finger millet. Scattered increases in the suitability of finger millet can also be noticed in semi-arid zones of Kitui, Machakos and Laikipia counties.

This significant upward trend of finger millet suitability within semi-arid zones could potentially continue into the end of the century thereby having a positive impact on food security within these counties, whilst maize suitability predominantly remains concentrated in central Kenya.

For the duration of the short rains, maize is predicted to experience a reduction in suitable areas and suitability scores in the near term and mid-century. For instance, in Northern Kenya, during the period between 1980 to 2009, suitability ranged at around 0.5 (50%). After an SIV fall of around -0.3 (-30%), therefore maize growing would be greatly challenged and the long-term cultivation would become unsuitable. In contradiction, historically, finger millet had little to no suitability throughout the majority of the counties and is predicted to increase by 0.2 (20%) on the coastline, leading to the SIV to range between 0.1-0.4 which indicates very low to marginal suitability. The rise in SIV of finger millet may be attributed to the increase in future rainfall (Figure 8) thereby achieving the minimum threshold for the crop to grow.

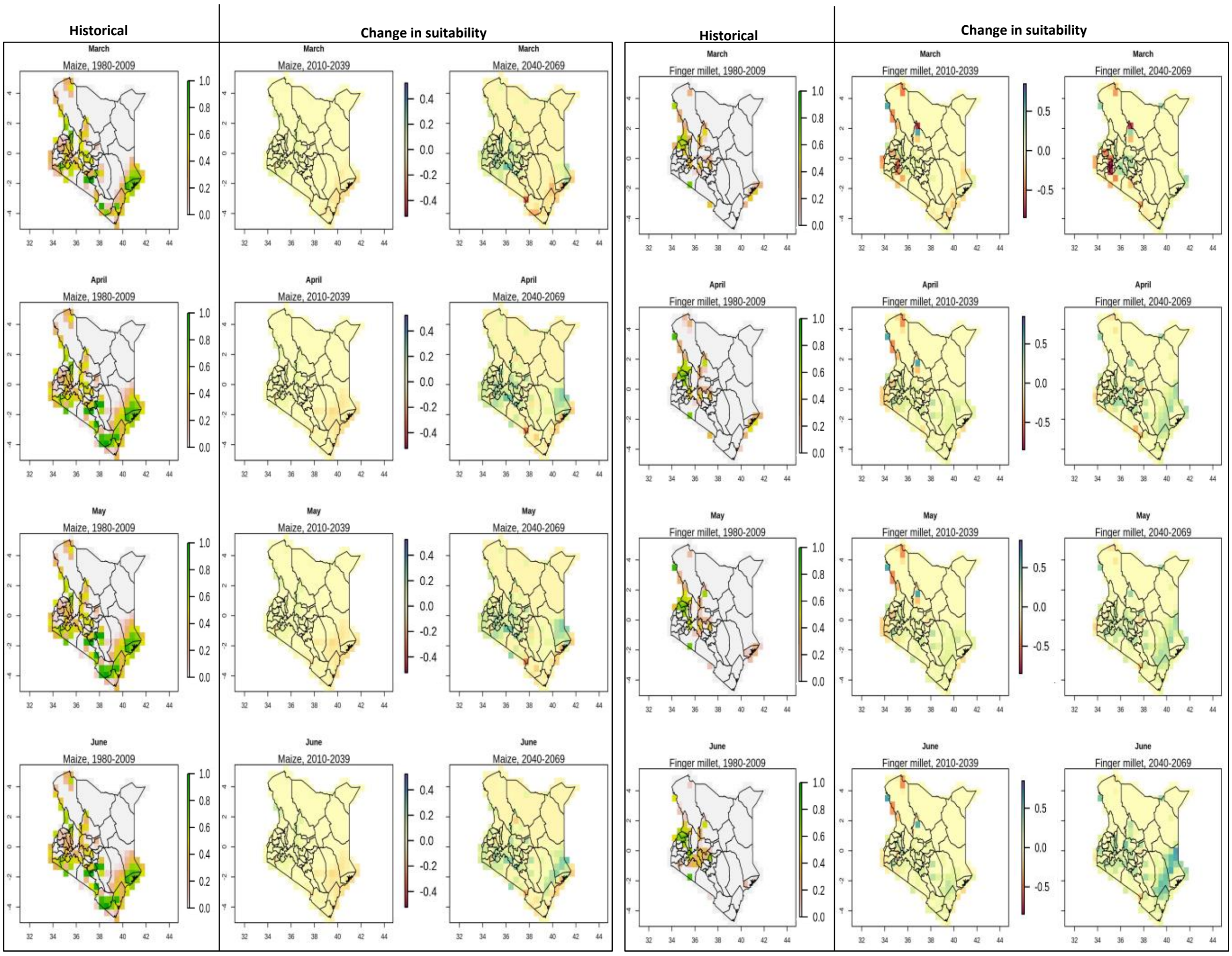


Figure 10: Historical and projected changes in spatial suitability distribution during the long rains for historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) under the RCP8.5 pathway for (LEFT) Maize and (RIGHT) Finger millet

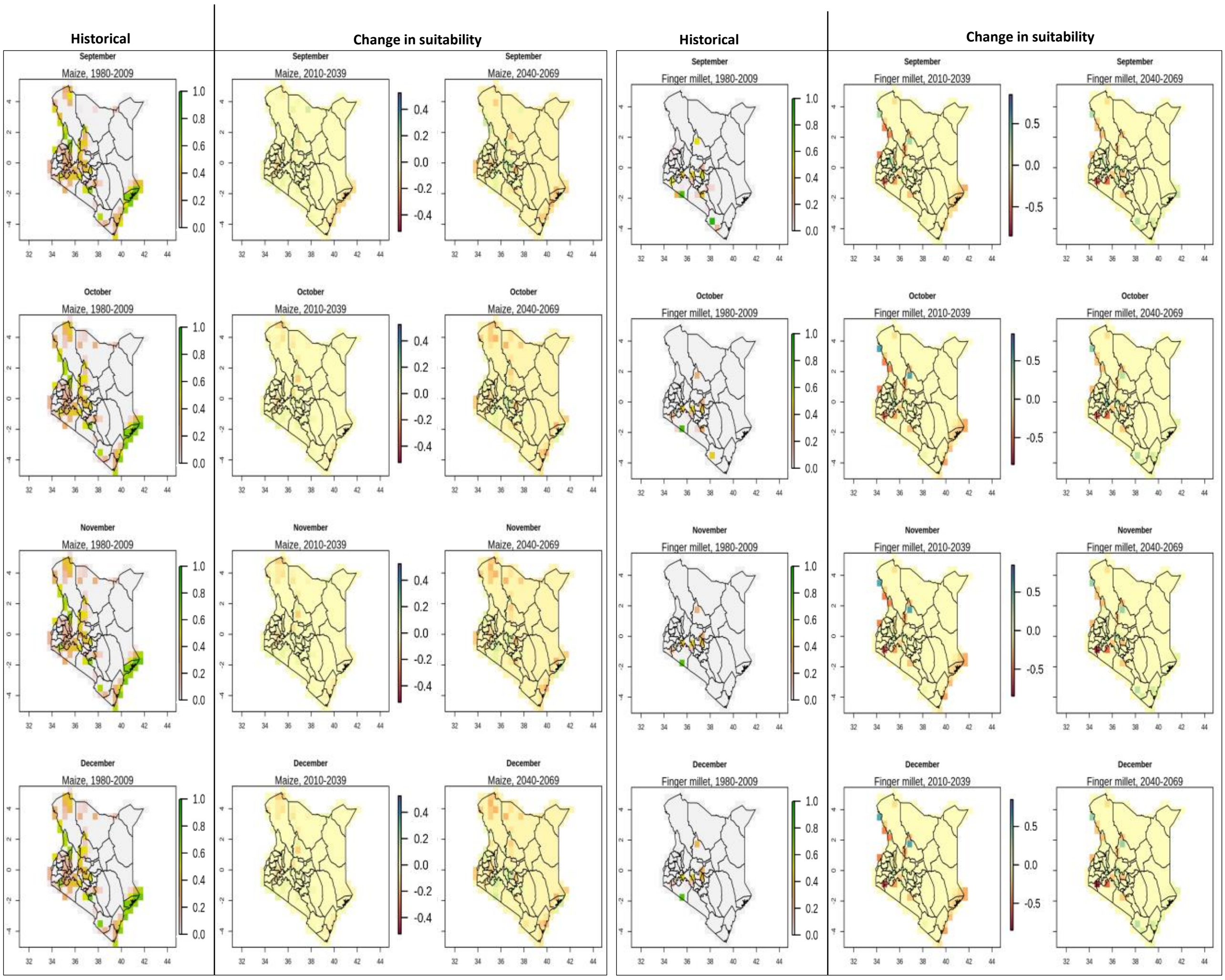


Figure 11: Historical and projected changes in spatial suitability distribution during the short rains for historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) under the RCP8.5 pathway for (LEFT) Maize and (RIGHT) Finger millet

4.2.1.2 Legume crops

The different nature of change in suitability of legumes compared to cereals was made evident in the Ecocrop suitability simulations of common bean and broad bean; in figure 12 and 13 respectively. Historically, the suitability of common bean was widespread, with very suitable conditions in central Kenya and marginal to suitable conditions along the coast and semi-arid counties in northeastern Kenya. It is interesting to note that common bean had the greatest spatial distribution of suitability during the dry season (July to September), peaking in August, whereby the crop was marginally suitably in the entirety of arid counties such as Garissa and Tana River. Similarly, broad bean also had extensive spatial suitability in August, during the peak of the dry season.

The change in the suitability of common bean was generally negative in both rainy seasons (Figure 12 and Appendix 3). A gradual fall in suitability is seen from the near term to the mid-century, for instance, during the 2010-2039 long rains, a fall of -0.2 (-20%) in the SIV is projected along the coast. Following this, suitability along the coast is predicted to fall by -0.4 (-40%) by mid-century, making the crop largely unsuitable. The same is true for counties within central and north-western Kenya such as West Pokot and Laikipia. However, during the dry season, arid counties such as Garissa, Wajir, Tana River and Lamu are expected to experience a substantial increase in the suitability of common beans especially by mid-century. Areas that previously had marginal suitability (20%-40%) are met with an increase in SIV of about 40% to 60%, making the crop suitable to very suitable in currently very arid, arid and semi-arid counties. These results feasibly open up a discussion of growing common beans during the dry season, which may come as a result of an increase in rainfall through this period.

The pattern in the change of suitability for broad bean is very similar to that of common bean. There is a scattered fall in suitability during the rainy seasons, however, the SIV is seen to increase greatly in northeastern Kenya, within the driest counties in the country. Broad bean and common bean have the lowest rainfall threshold of the five crops used in this study. This may contribute to the increasing suitability as the rainfall over arid regions of the country is predicted to decrease.

Currently, these legumes are planted during the onset of rains starting in March and October, while the dry season is used to grow crops such as onions, cabbage and kale (Farm Africa, 2019). With the understanding of different facets of food security, climate change is playing an increasingly prominent role in determining the level of food security within communities. For this reason, growing common bean and broad bean in the dry season could have the potential to improve the state of food security amongst communities living in arid and semi-arid counties. The introduction of these crops into the cropping system during this off-season would also benefit the soil in preparation to grow cereals in the rainy seasons. This is due to legumes having nitrogen-fixing properties which improve the fertility of the soil.

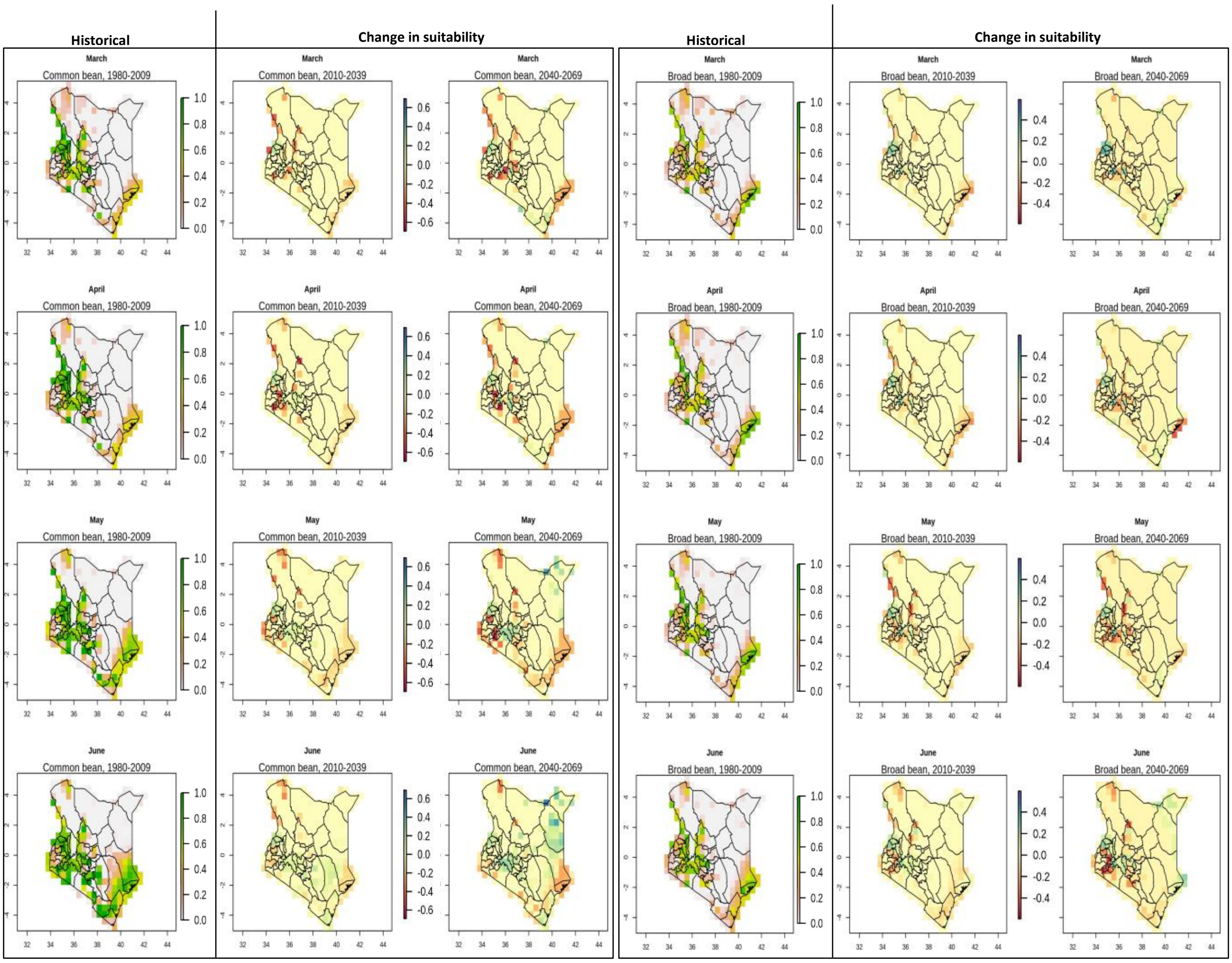


Figure 12: Historical and projected changes in spatial suitability distribution during the long rain season for historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) under the RCP8.5 pathway for (LEFT) Common bean and (RIGHT) Broad bean

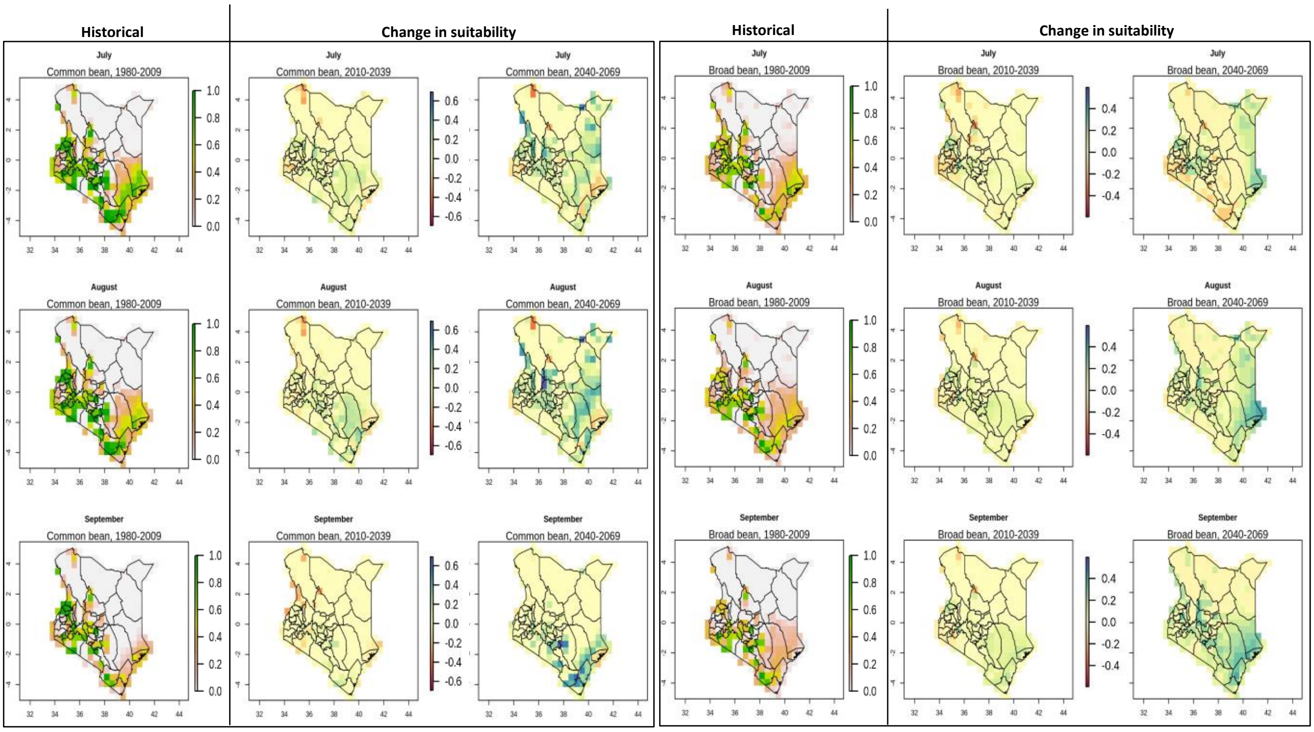


Figure 13: Historical and projected changes in spatial suitability distribution during the dry season for historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) under the RCP8.5 pathway for (LEFT) Common bean and (RIGHT) Broad bean

4.2.1.3 Root crop: Sweet Potato

The change in crop suitability between historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) for sweet potato is presented in Figure 14. The historical suitability of sweet potato is very marginal and is only concentrated within central Kenya. During the long rains, sweet potato is very suitable in counties such as Bungoma and Busia, with marginal suitability in counties such as Nyeri, Laikipia, Nyandarua and Kirinyaga. Scattered areas of very marginal and marginal suitability extend up to Turkana, with SIV between 30% and 60% along the coast. During the dry season in July and August, there is a greater area of suitability scores in central and northeastern Kenya, compared to the rainy season.

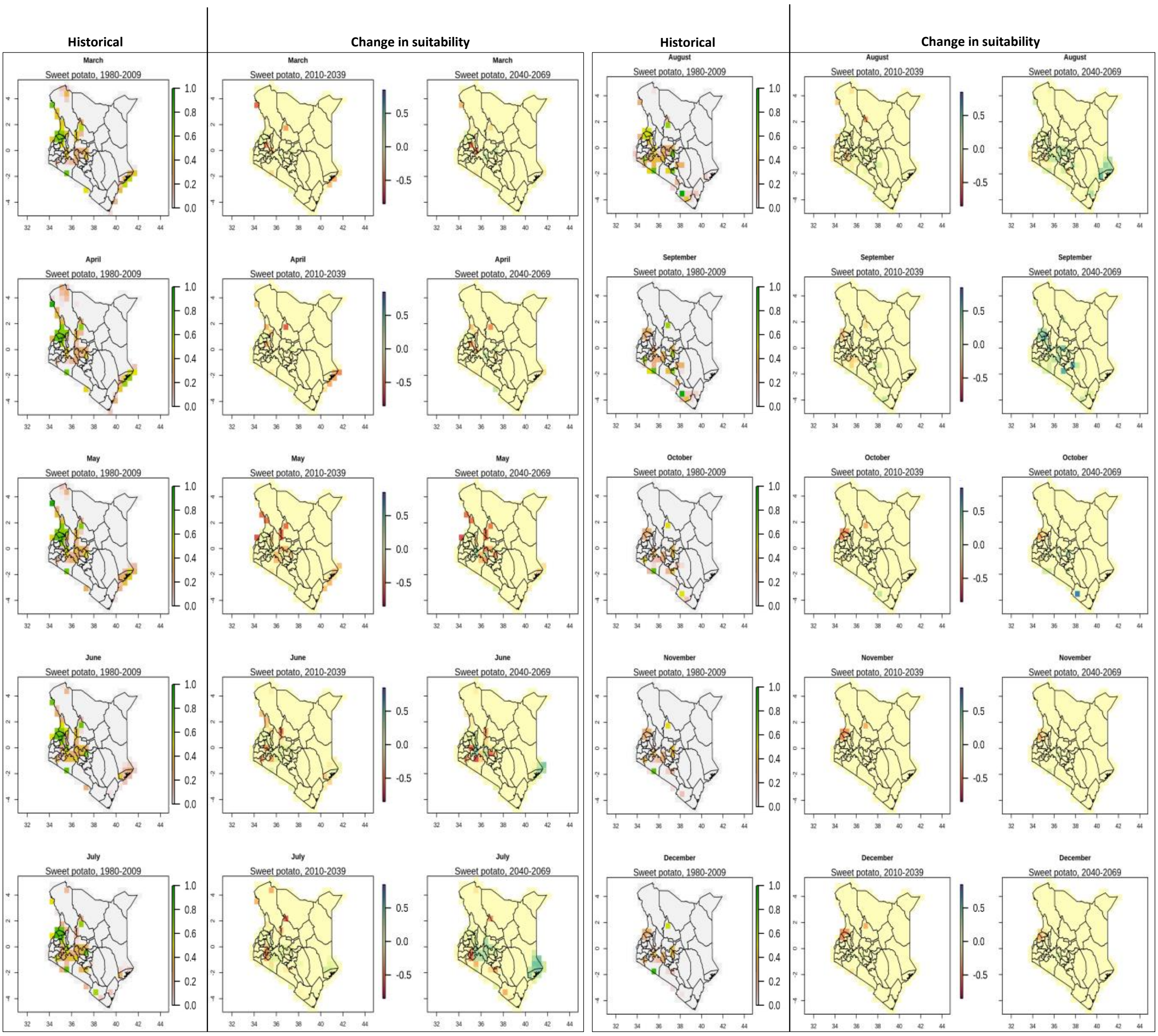


Figure 14: Historical and projected changes in spatial suitability distribution during the dry season for historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) under the RCP8.5 pathway for Sweet potato

The change in suitability is minimal with a general reduction in SIV during the wet seasons. For instance, in April in the near future, suitability along the coast falls by almost -0.4 (-40%) in areas that were historically marginally suitable, therefore leaving the crop unsuitable to grow. During the short rains, there is very little change in suitability. However, during the dry months of July, August and September, by mid-century, a rise in the suitability of around 0.2 (20%) to 0.4 (40%) is predicted within a few counties such as Machakos, Nakuru and Laikipia. The climate suitability scores of sweet potato question the importance that climate change might have on the suitability of growing this root crop. Other factors such as soil properties may play a greater role in determining the ability to grow sweet potato in the future.

4.2.2 Change in suitability under RCP4.5 climate conditions

Crop suitability calculated based on climate data under RCP4.5 is a potential result of future carbon emissions being reduced by half. Historical crop suitability is independent of the RCP pathways considered, and therefore provides a good point of reference to compare the change of suitability between RCP4.5 and RCP8.5. This section will explore the change in crop suitability for maize, finger millet, common bean, broad bean and sweet potato under RCP4.5 climate conditions.

4.2.2.1 Cereal crops

The Ecocrop suitability for maize and finger millet during the long rains are presented in Figure 15. Historically, maize was suitable through many counties that are characterised as humid to semi-humid (see section 4.2.1.1). Under RCP4.5, future suitability of maize indicates an increase within these counties, especially during April, May and June. As a result, the planting of maize could potentially shift from March to April due to greater suitability in the latter month. This may come as a result of delayed long rains. For instance, between April to June, there is an increase in suitability area in arid counties such as Garissa and Tana River with an SIV increase of around 0.3 (30%) in areas that previously have an SIV between 0.2 (20%) to 0.3 (30%) during the mid-century period. There is a continuing increase in SIV from the near-term period to the mid-century period.

In contrast, finger millet, which was previously suitable in scattered areas in western Kenya is predicted to experience a fall in SIV. This isolated reduction in SIV in western Kenya could be attributed to the scattered change in rainfall during future periods. The only positive change in SIV is concentrated in and around Lamu county, whereby by mid-century, an average increase of around 0.3 (30%) would be experienced within the county. Based on historical SIV, conditions would then become suitable for finger millet.

Maize in future short rains (Figure 6) will not experience a similar increase in SIV as seen during the long rains. Instead, by both future periods, counties in western and central Kenya are projected to face a reduction in SIV as great as -0.4 (-40%) within several locations in the country. However, the coast will experience a rise in SIV. Historically, suitability along the coast is very suitable, so that with further increase in SIV, maize would experience excellent suitability along this stretch. This disparity in the spatial distribution of a change in maize suitability could be attributed to the fact that temperature rise, as seen in figure 5, is predominantly higher in the western and central parts of the country and therefore exceeding maximum temperatures at which maize strive.

Finger millet is projected to have no significant changes of suitability area and suitability score in the near-term and mid-century (Figure 16).

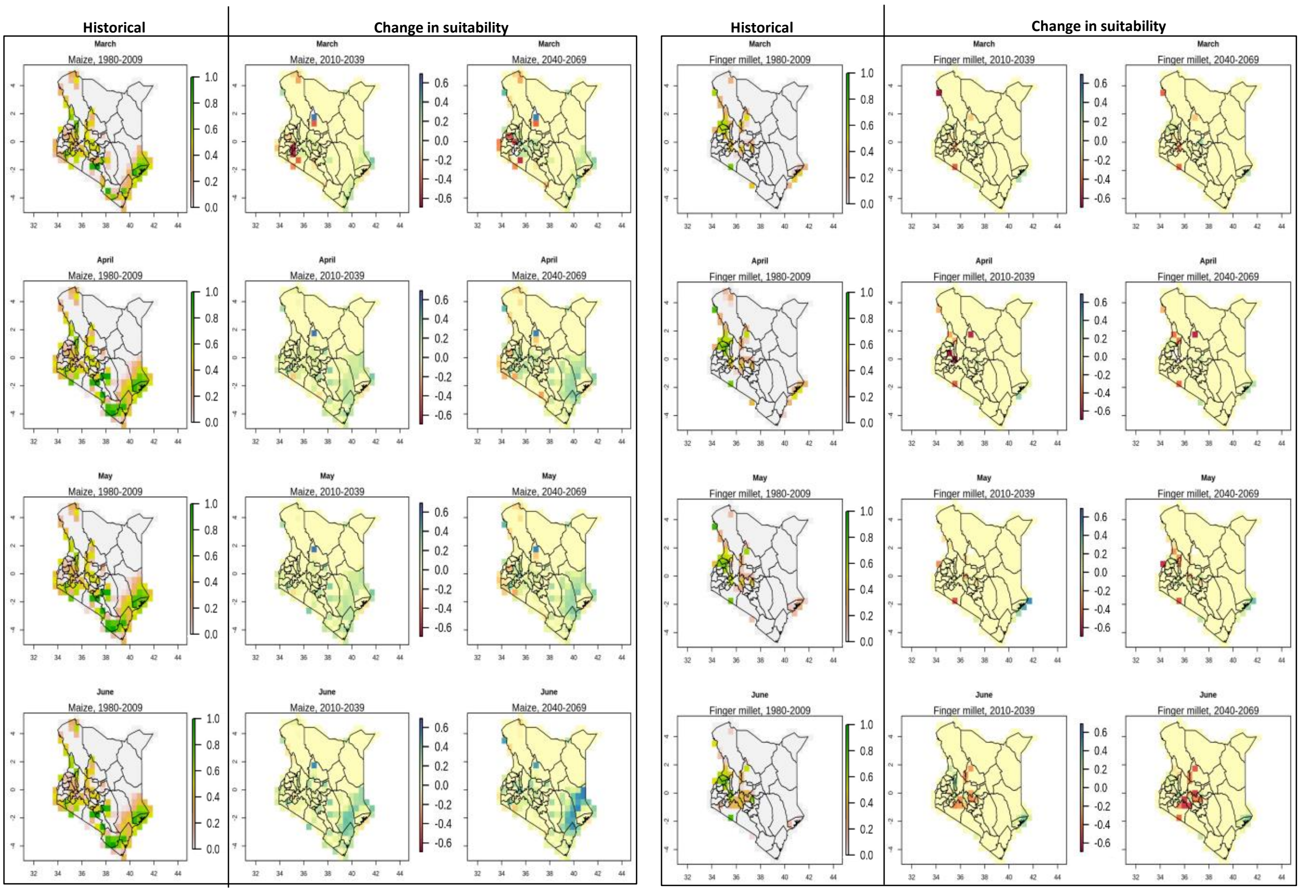


Figure 15: Historical and projected changes in spatial suitability distribution during the long rains for historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) under the RCP4.5 pathway for (LEFT) Maize and (RIGHT) Finger millet

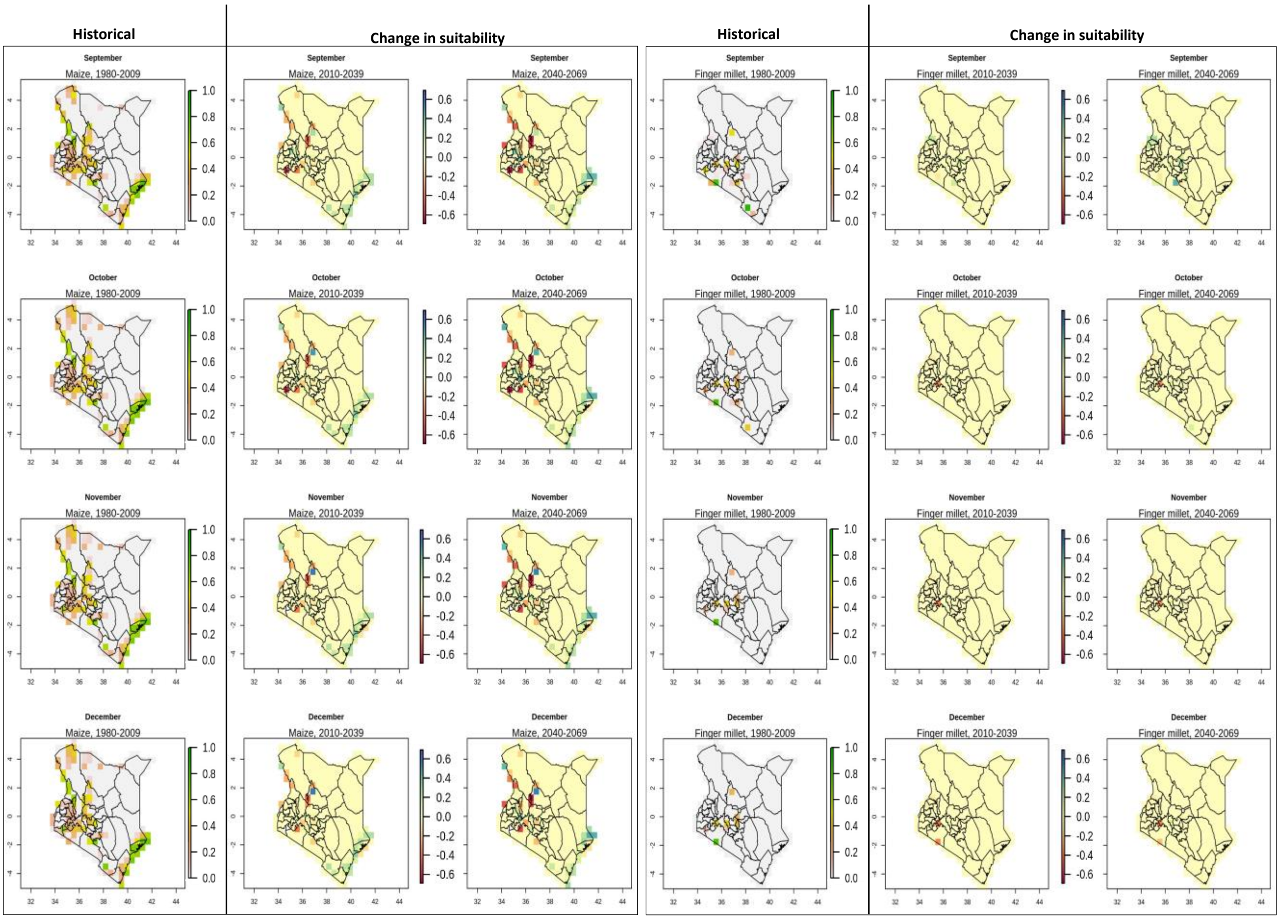


Figure 16: Historical and projected changes in spatial suitability distribution during the short rains for historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) under the RCP4.5 pathway for (LEFT) Maize and (RIGHT) Finger millet

4.2.2.2 Legume crops

Historically, common bean has the highest suitability in terms of area and suitability scores during the dry season between July and September. Under RCP4.5 future climate conditions (Figure 17), the suitability in July increases largely in both future periods. The suitability area increases into more arid counties such as Wajir and Mandera. The SIV also progressively increases in the near-term and mid-century periods. For example, in Tana River county, during the near-term period, the average change was around 0.2 (20%), while in the mid-century period it ranged between 0.3 (30%) to 0.4 (40%). Broad bean (figure 16) follows a similar pattern during the dry season, with a substantial increase in the area in which the legume becomes suitable to grow. Unlike common bean, the increase in SIV is evenly distributed throughout counties in eastern and central Kenya and extends till September. This could give farmers the option to plant at the beginning of the currently classified dry season, which starts in July, or they could potentially start planting in September, rather than October, in anticipation of the short rain.

Similar to the trend seen in RCP8.5, during the long rains (Appendix 4), the suitability of common bean is projected to fall in many of the counties, with the greatest decrease in western and central Kenya, of up to a -0.4 (-40%) SIV reduction in regions that previously had excellent suitability. In both future periods, there is a decrease in SIV along the coast, with -0.1 (-10%) and -0.2 (-20%) in the near-term and midcentury periods, respectively. Broad bean also experiences a reduction in SIV in western Kenya, however, within counties along the coast, such as Kwale and Kilifi there is a slight increas7777777e in suitability scores of less than 0.2 (20%). With the region previously having marginal suitability, a very slight rise in SIV would make broad bean suitable to be grown along the coast during the long rains.

The changes in suitability of common bean and broad bean during the short rains (Appendix 5) are very similar to the changes that are predicted to take place for the long rains.

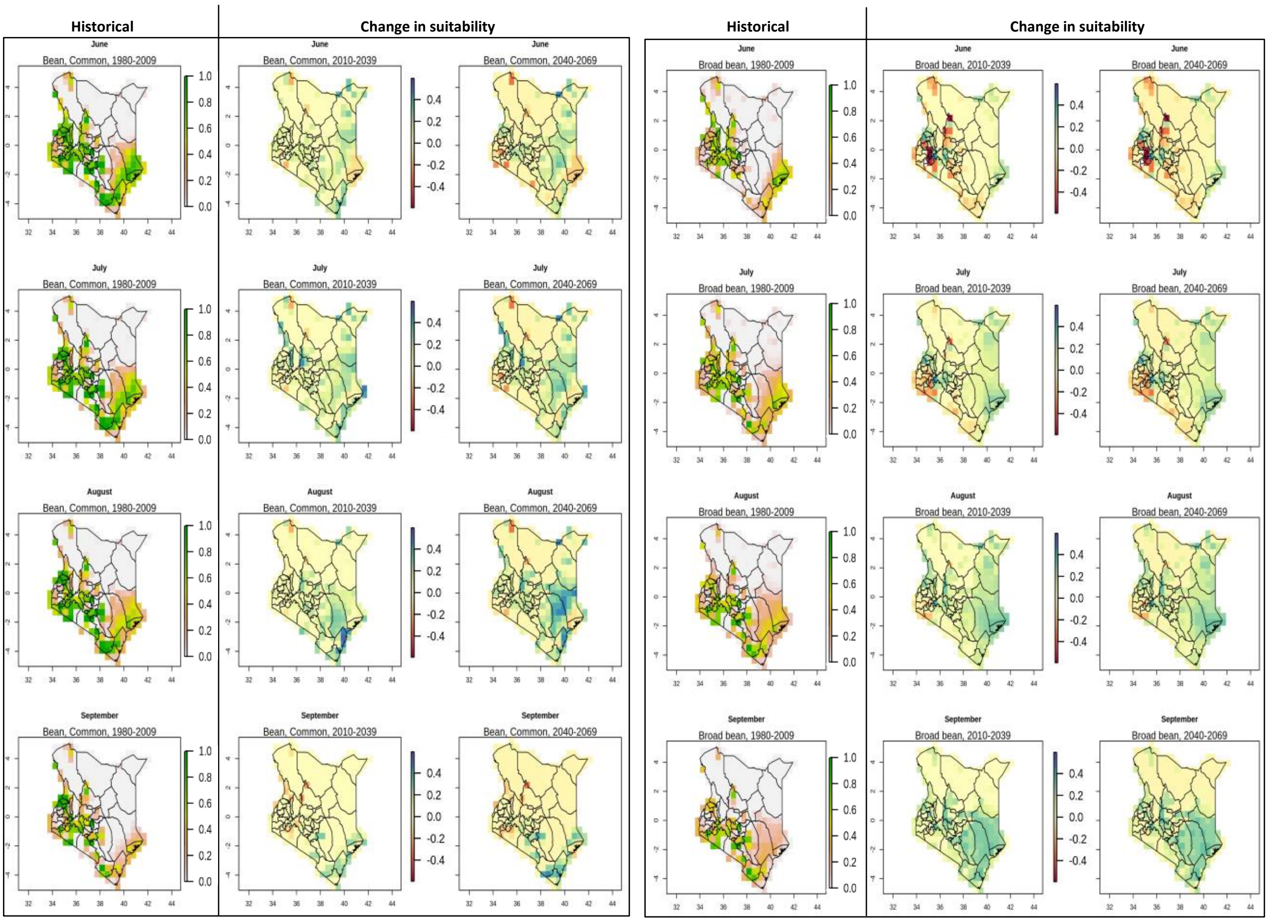


Figure 17: Historical and projected changes in spatial suitability distribution during the dry season for historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) under the RCP4.5 pathway for (LEFT) Common bean and (RIGHT) Broad bean

4.2.2.3 Root crop: Sweet potato

The change in crop suitability between historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) for sweet potato is presented in Figure 18. Sweet potatoes are generally planted in March, on the onset of the long rains, and harvested in July. However, climate suitability indicates a very scattered suitability across the country. Under the RCP4.5 climate pathway, it is projected that the SIV will fall in both, near-term and mid-century, with the latter facing a more severe decline. The majority of these reductions occur during the long rain season. For instance, the SIV in March (planting) will fall by as much as -0.5 (-50%) in counties such as Nandi. However, on the coast, especially in Lamu, the SIV is expected to increase from March to July.

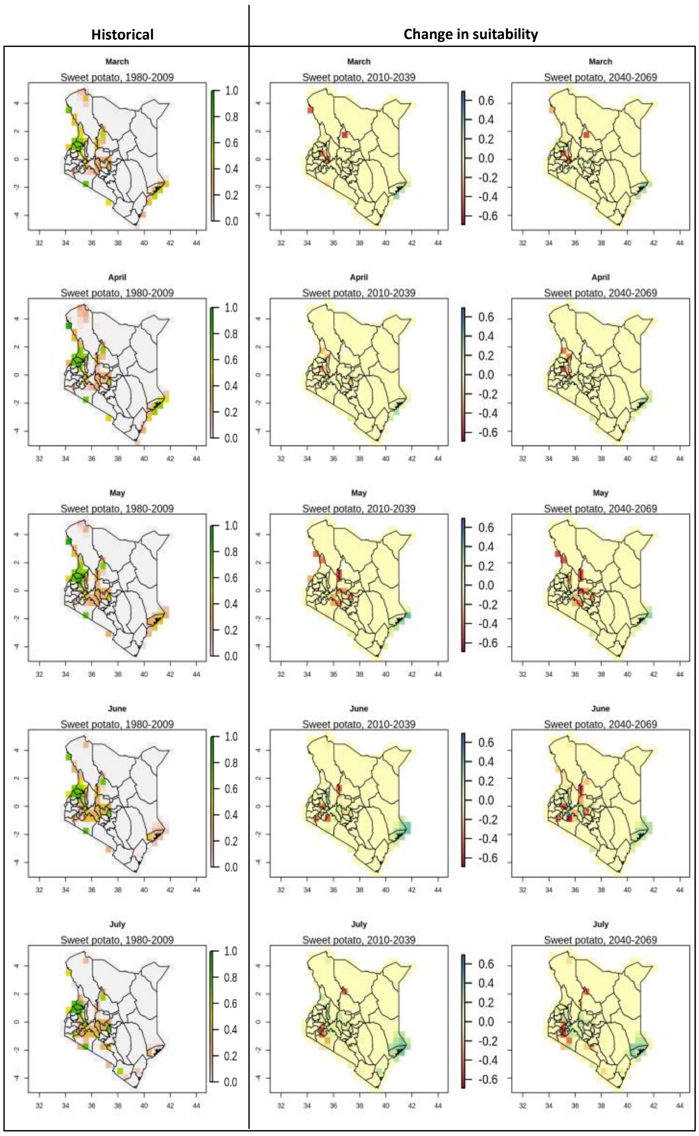


Figure 18: Historical and projected changes in spatial suitability distribution during the dry season for historical (1980-2009), near term (2010-2039) and mid-century (2040-2069) under the RCP4.5 pathway for Sweet potato

4.3 Soil pH and climate suitability

Despite the ongoing role that climate change has in impacting crop suitability, poor soil conditions in sub-Saharan Africa also pose major limitations to the growth of crops. For this reason, this section of the results plays a vital part in understanding the capacity at which soil pH can have on deterring climate-only defined crop suitability. QGIS was used to determine the overlap between climate suitability and the pH tolerance of cereals (maize and finger millet), legumes (common bean and broad bean) and a root (sweet potato) at two levels of suitability. Unsuitable conditions represent areas where climate suitability was zero and soli pH is beyond the crops threshold. Results are for April since all five study crops are commonly planted in anticipation of the long rains.

4.3.1 Cereals

Maize grows in slightly acidic soils, with an optimum pH of around 6. This can be found in wet and humid regions where rainfall is frequent enough to cause the soil to acidify and restrains it from becoming too alkaline. Suitable conditions occur when pH is between 5.5 and 7.3 and SIV> 0 overlap, while optimum suitability occurs when 6 < pH < 6.5 and SIV > =0.4.

Climate suitability and the tolerant pH range for maize closely align, with both being concentrated in western and central Kenya, as well as counties along the coast (Figure 19). Optimum suitability can be found in counties in central Kenya, such a Laikipia, as well as the semi-arid zone on Kitui county. With maize being a staple food in the country, having both climate and pH suitability in these regions would highly benefit smallholder farmers who can not afford pH amendments or methods to meet the water needs of the plant, such as irrigation. There is neither pH nor climate suitability in eastern and northern Kenya, however, maize is still a staple food in these counties. This would suggest that the crop is grown in areas

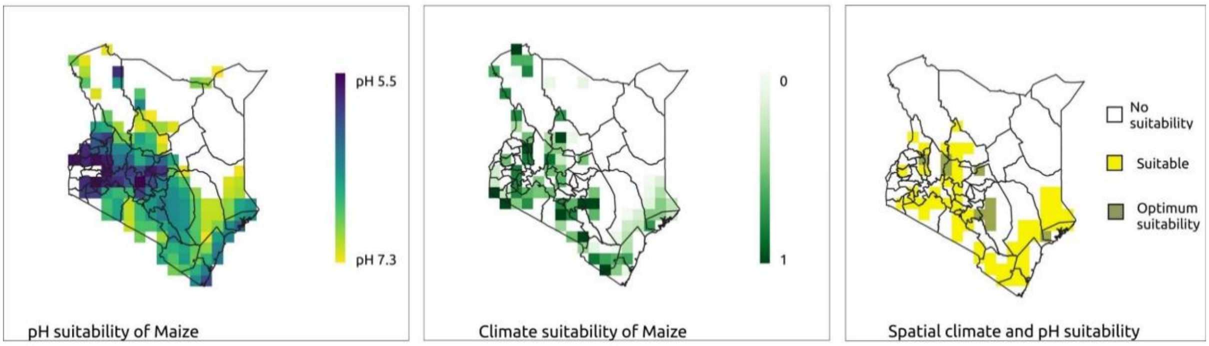


Figure 19: Left: suitable pH range to grow maize. Centre: Climate suitability of maize in April 2010-2039 as calculated through Ecrocrop. Right: Spatial distribution of the overlap of pH and climate suitability under suitable and optimum suitable conditions.

that are unsuitable and maybe lead to degradation of the land as a result of extensive soil alterations.

Finger millet has a greater pH range in comparison to maize, with pH suitability being spread across the majority of the counties in the country (Figure 20). pH and climate suitability are presented as the spatial area where pH is between 5 and 8 with the SIV greater than 0, while optimum suitability is pH 6 to 6.5 where SIV is greater than 0.4.

Due to the low and scattered climate suitability, the overlap between these two variables is only concentrated in western Kenya, with only a very small area achieving optimum suitability. Finger millet may not be able to serve as a staple food for many, but rather as a supplement to maize as a staple food for smallholder farmers. The results also point to the importance of climate suitability, such that if soil pH was used exclusively to determine suitable growing areas, it would fail to capture finger millet climate unsuitability in many parts of the country.

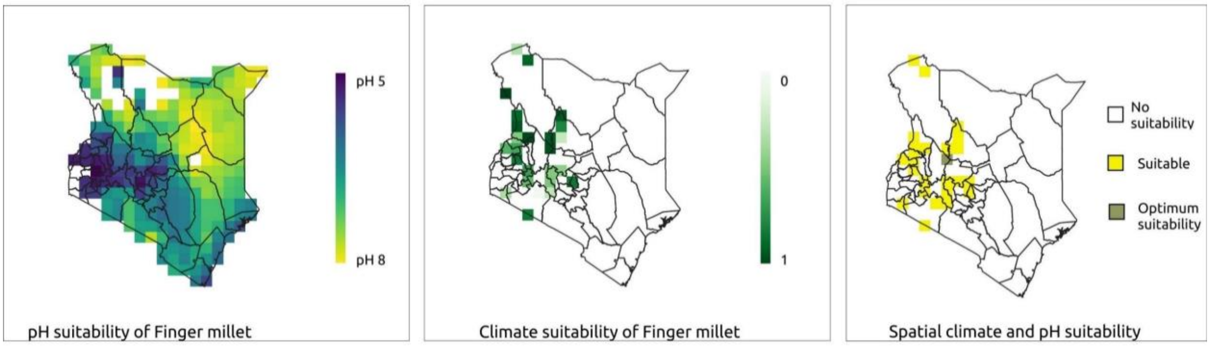


Figure 20: Left: suitable pH range to grow finger millet. Centre: Climate suitability of finger millet in April 2010-2039 as calculated through Ecrocrop. Right: Spatial distribution of the overlap of pH and climate suitability under suitable and optimum suitable conditions.

4.3.2 Legume crops

The suitable pH of broad beans is relatively higher than the other crops used for this study, ranging from 6.5 to 9. This was spread across arid and semi-arid regions due to the less rainfall which allows for more alkaline soils. Suitable conditions include the area where pH is between 6.5 and 9, with SIV greater than 0, and optimum suitability was computed where pH is greater than 7 and less than 8 and SIV being greater than 0.4.

During April of the near term period, the climate suitability is prominent in western and northwestern Kenya. This leaves the area where climate and pH suitability are very scattered around the country (Figure 21). However, under future climate projections seen in section 4.2.1.2, the SIV in arid and semi-arid zones is seen to increase, in counties such as Garissa and Tana River. Therefore, within the mid-century period, there is likely to be a greater area where pH and climate suitability coincide, providing better overall suitability to plant broad beans in April. In addition, rainfall is not expected to drastically rise in the arid zones within the long rains, therefore soil pH can be expected to remain similar to current projections due to the limited role of leaching and thereby soil acidification.

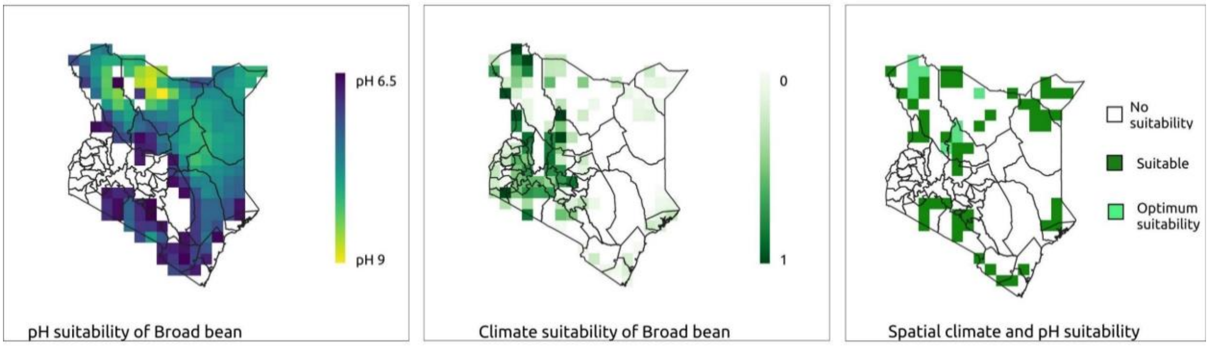


Figure 21: Left: suitable pH range to grow broad beans. Centre: Climate suitability of broad bean in April 2010-2039 as calculated through Ecrocrop. Right: Spatial distribution of the overlap of pH and climate suitability under suitable and optimum suitable conditions.

Figure 22 shows the pH range for growing common bean, the climate suitability of planting common bean in April and the overlap between pH and climate suitability. Suitable conditions are an overlap of pH between 5 and 7.5 and SIV (0-1), while optimum suitability was calculated when 6.5 < pH <7 and SIV > 0.4. In comparison to broad bean, common bean has a smaller growth range of pH levels.

The combined suitability of common bean is heavily concentrated in western and central Kenya, as well as Lamu and Kwale counties at the coast. There are also several areas with optimum suitability, for example, Narok. Despite common bean having greater climate suitability in the dry season, figure 21 suggests a large area in the majority of the agricultural producing counties to be climate and pH suitable to grow common beans. These results also show that climate is the constraining factor, more than soil pH, especially since climate also plays a role in determining pH levels.

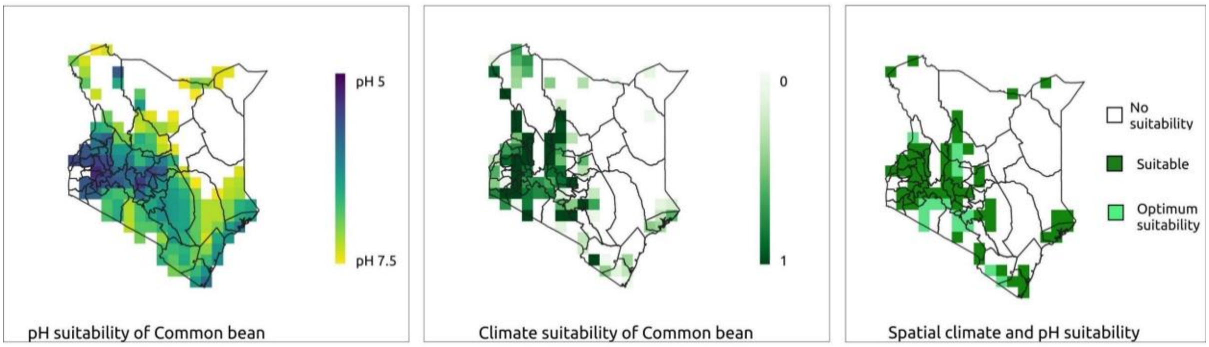


Figure 22: Left: suitable pH range to grow common beans. Centre: Climate suitability of common bean in April 2010-2039 as calculated through Ecrocrop. Right: Spatial distribution of the overlap of pH and climate suitability under suitable and optimum suitable conditions.

4.3.3 Root crop: Sweet potato

Sweet potato grows in relatively acid soils which are concentrated within a few counties in western Kenya. Suitable conditions include the area where pH is between 4 and 6.4, with SIV greater than 0, and optimum suitability was computed where pH is greater than 5.5 and less than 6 and SIV being greater than 0.4 (Finger 23).

The combination of pH and climate suitability results in a very small area that is suitable to grow the root crop in counties such as Laikipia and Nakuru. However, in the majority of this area, optimum suitability is achieved, which would indicate high yields would be achievable. This presents the opportunity for such counties to become the pivot of sweet potato production, which could supplement major staple foods.

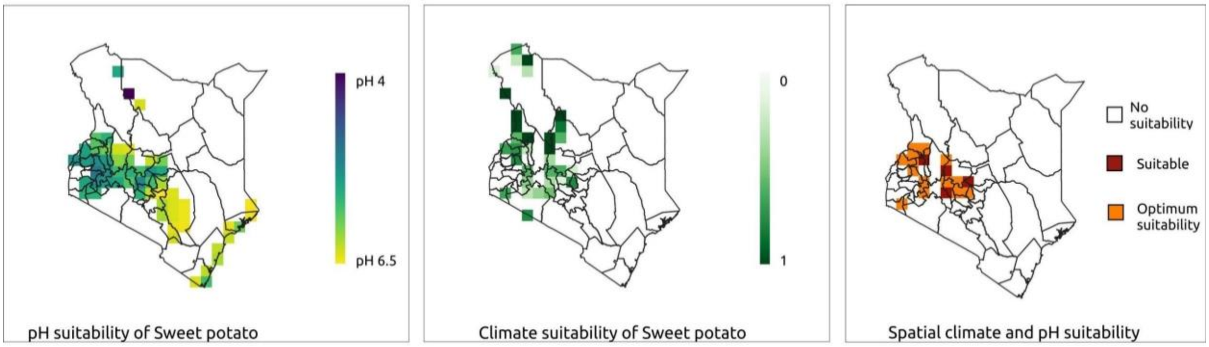


Figure 23: Left: suitable pH range to grow sweet potato. Centre: Climate suitability of broad bean in April 2010-2039 as calculated through Ecrocrop. Right: Spatial distribution of the overlap of pH and climate suitability under suitable and optimum suitable conditions.

Chapter five: Discussion

5.1 RCP8.5 vs RCP4.5

The RCP8.5 climate pathway leads to a worst-case scenario in terms of changing crop suitability and will come about due to little or no intervention towards the reduction of GHG emissions. The RCP4.5 pathway would be more favourable as crop suitability will not be as adversely impacted by climate change, as seen in sections 4.2.1 and 4.2.2. This section will outline the benefits to food systems if GHG emissions were reduced.

During the long rain season, there is a stronger rise in maize suitability under RCP4.5 in both future periods. For example, in April in the near-term and mid-century, there is a greater rise in suitability in semi-arid counties on the RCP4.5 pathway. In contrast, using the RCP8.5 climate pathway, the suitability of maize does not experience a drastic increase. The rise in suitability may lead to more smallholder farmers who depend on ideal weather conditions, being able to plant maize during the long rain season under RCP4.5. As a consequence, production could potentially rise and contribute to the food security of the growing population in Kenya. In contrast, the very marginal increase in suitability under RCP8.5 may not be sufficient to sustain the food security of people in Kenya.

During the short rains, under RCP8.5, maize is predicted to experience a reduction in suitable areas and suitability scores in the near term and mid-century. This may be due to the higher temperatures especially in counties that were historically suitable to grow maize. However, under RCP4.5, despite the reduction in SIV in western and central Kenya, the coastal counties are projected to experience an increase in suitability. If food systems do not diversify and maize remains as the major staple food, RCP4.5 could offer food security relief.

The historical spatial distribution of climate suitability to grow finger millet was relatively low in comparison to maize. However, on the RPC8.5 climate pathways, there is an increase in suitability during the short rains in central and coastal counties. The increasing trend in suitability could possibly carry through to the end of the century. In contradiction, on the RCP4.5 pathway, there was a very marginal change in suitability which was predominantly negative. This may suggest the resilience of finger millet to harsher future climates on the RCP8.5 path and could provide a complementary alternative to cereals such as maize.

Both legumes studied in this project are predicted to experience a substantial rise in SIV throughout the majority of the counties, including semi-arid and arid counties. This trend is common in both RCP4.5 and RCP8.4, however, there is a higher rise in SIV along the former pathway. Despite this, the result indicates that common bean and broad bean are suitable to grow under both future climate projections. Food insecurity encompasses four pillars, with one being no access to nutritious food. People in sparsely populated arid counties have limited access to markets as well as suitable conditions to grow rainfed crops. The potential to grow these legumes in arid regions could provide an opportunity to improve food security in these counties.

Finally, the change in climate suitability of sweet potato did not differ significantly between the RCP8.5 and RCP4.5 pathways. The rise in suitability under both climate pathways was concentrated in Lamu county along the coast, with an increase in SIV of around 0.4 (40%) as well as scattered increases in central Kenya which are more prominent under the RCP8.5 pathway. Currently, sweet potato is planted in March for the onset of the long rains, however historical and future climate suitability is very low throughout the country. This provides an indication that smallholder farmers may be considering other factors that have a more impacting result on yields, for example, soil properties or waterlogging.

5.2 Integrating orphan crops into Kenyan food systems

The results of this study outlined the prefered cropping season, in terms of climate suitability for each of the crops. This offers insights into the potential for diversifying cropping systems, instead of monoculture of major crops to strive towards a more resilient and food secure country. For instance, in many counties, maize is grown during the long and short rains. However, future suitability projections under both, RCP8.5 and RCP4.5, indicate a decrease in climate suitability to grow maize during the short rains in crucial maize producing counties. The continuation of the production of maize during the short rains may still be possible, however, will not be sustainable in the long run, especially for smallholder farmers who can not afford to cope with the shocks and stresses associated with climate change. Commercial farmers have the ability to dampen the effect that climate change has on the suitability of the crops through irrigation systems, growing in greenhouses or using genetically modified seeds. An alternative would be to use the short rains to grow a crop that has better suitability in the future. This study was limited to only five crops, none of which had a strong enough suitability to be recommended as a crop that could be used to supplement maize during the short rains. However, evidence provided in the results exhibit a range of suitability change, which suggests that current uncommon crops, which are less sensitive to climate stresses may offer a good complementary alternative

In order to reduce the stress and over-reliance on maize during the long rains (Khoury et al, 2014), orphan crops such as sweet potato can be grown simultaneously. Despite not having a great spatial distribution of suitability, as shown in the results of the pH and climate SIV, much of the area that is classified as suitable achieves optimum suitability. Therefore, these counties that are predominantly in western Kenya can potentially provide as baskets for sweet potatoes. The momentum of such initiatives has increased in the past few years. For instance, the International Potato Center (CIP) targeted counties in western Kenya, such as Kisumu and Nyanza to promote orange-fleshed sweet potato. This project was established with the aim to create a unique partnership between agriculture and health. It was found the over 50% of women in this region had diets that were deficient in vitamin A. In order to improve health in the area, CIP earmarked 35,000 households to receive training on diversifying their diets through incorporating sweet potato (CIP, 2017).

Crop rotation with legume orphan crops, such as broad beans, can also contribute to achieving food security. With climate projections indicating a slight increase in rainfall during the dry season, water requirement thresholds of broad beans are predicted to be achieved. This resulted in an increase in suitability to plant beans during the dry season. The possibility to rotate maize with common bean or broad bean not only utilizes the dry season to produce nutritious food but also improves soil quality as legumes are nitrogen fixating plants. The increase in suitability was evident in many arid and semi-arid counties. Being able to grow these legumes in such remote areas would improve access to food for the population that live in these areas and depend heavily on pastoral farming. Practices such as intercropping and rotations are forms of climate-smart agriculture, which would result in more sustainable cropping systems in the long run (Chivenge et al., 2015).

During the fiscal year of 2019 and 2018, USAID's total food aid contribution accounted for $102.1 million and $89.3 million, respectively. This equates to an average of 60,000 metric tons of food (USAID, 2020). However, if investments were channelled into enhancing smallholder agriculture through climate-smart agriculture as mentioned above, there is potential to increase productivity. As a result, income gaps, price volatility and price inflation could reduce in the country.

5.3 Model limitations

The climate suitability of crops is vital to understanding how major and minor crops would be affected under future climate change projections, in terms of the physical processes, rather than actually crop yields. Furthermore, since Ecocrop is an empirical rather than a process-based model, it is unable to produce context-specific outcomes based on detailed biological and physical processes (Roberts et al., 2017). Rather, the outcomes of this study emphasize the amplitude of change, however, this is not necessarily the primary message that can be used to inform policy-makers and governmental organisations. Instead, a strong trend in the change in suitability could provide vital information about future agriculture in Kenya. This is due to the fact that the amplitude of change can deviate between the different GCM inputs.

For example, Figure 24 represents the SIV for maize under RCP8.5, for April, between the near-term period. The NOAA-GFDL model projects the highest suitability in terms of scores and spatial distribution, compared to the HadGEM2-ES model which is less spatially distributed. However, the trend between the four GCMs is strong, such that there is maize suitability in counties along the coast and central and western Kenya. Therefore, using the mean suitability values from the four GCMs provided this study with a more robust estimate of suitability scores and the spatial distribution of these results.

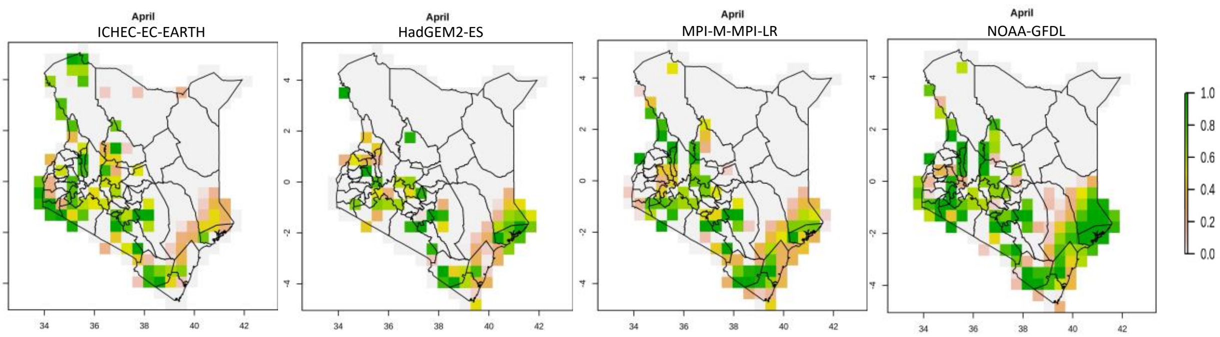


Figure 24: Suitability index values for Maize in April during the near-term period (2010-2039) for four GCMs

5.4 Beyond climate suitability

Improved crop suitability could directly affect the two pillars of food security; food availability and stability; as more smallholder farmers would see ideal conditions to grow a crop.

However, it is important to acknowledge the many facets that could affect crop production. Within this study, the role that soil pH had in determining where crops were suitable to grow became evident. For instance, broad beans had very suitable climate conditions in western Kenya, on the contrary, pH levels in this area were lower than the tolerance levels of the legume. For this reason, there was no suitability when pH and climate suitability were combined. In this way, we can understand how different aspects could affect crops, such as soil properties, slope and crop varieties. Climate change is also contributing to the spread of pests that heavily impact food availability. One major example is the desert locust invasion that was experienced in Kenya between the end of 2019 to early 2020. This upsurge was a result of one of the strongest IOD experienced in 60 years, which fueled heavy and widespread rains contributing to the spread of large swarms across the country. These desert locusts were responsible for tremendous agricultural losses which posed a greater threat to food security in the country (Salih et al., 2020).

In addition to climate change adaptation and mitigation, county and national support are vital in achieving food security. Such interventions could include the development of markets and infrastructure, with an aim to improve access to food for people in report areas. Food utilization can improve through the integration of nutrition-sensitive value chains. Avenues that promote diversification of diets and encourage mixed allocation for crop production with orphan crops can help achieve better utilization of food.

Chapter Six: Conclusion

This study assessed the impacts of climate change in terms of future crop suitability, for major and minor crops in Kenya under future climate change projections. This was achieved through the calculation of crop suitability of cereals (maize and finger millet, legumes (common bean and broad bean) and a tuber root (sweet potato) using the Ecocrop suitability model. The suitability model used three climatic variables; minimum and mean temperature and rainfall; under RCP8.5 and RCP4.5 which was obtained from four downscaled GCMs available through CORDEX. Suitability simulations were run for three time periods: historical (1980- 2009), near term (2010-2039) and mid-century (2040-2069). This study acknowledges the complexity of crop suitability and therefore included soil pH as a variable that impedes crop growth in Kenya. QGIS was used to map regions where crop pH thresholds were met concurrently with climate suitability to get an understanding of the role pH has in determining suitability.

6.1 Key findings

Under RCP8.5, future temperatures are projected to increase by 2°C - 2.5°C. Rainfall along the RCP8.5 pathway is set to increase throughout the year, with the greatest increase occurring during the peak of both rainy seasons (April and November). In contrast, under RCP4.5, the country is projected to experience a 0.5°C - 1°C temperature increase by mid-century, with the greatest temperature rise occurring during the dry season (June to September). The rainfall trends under RCP4.5 are very similar to those under RCP8.5, however, projections of increases and decreases are to a smaller extent. May and June are projected to get drier under both RCP's, suggesting that the dry season would be getting longer.

Despite maize being grown in the long and short rain seasons in Kenya, historical suitability during the short rains is low and is projected to decrease. This is evident in both RCP4.5 and 8.5. In contrast, during the long rains, by the mid-century period, the suitability of maize is projected to increase by around 0.2 (20%) in central and coastal Kenya. The climate suitability outcomes under RCP4.5 indicates that a reduction in GHG emissions could provide some food security relief in comparison to RCP8.5. This is due to the maize being projected to have higher suitability by mid-century under RCP4.5. For instance, in April between the mid-century period, within coastal counties, the SIV increase is 0.1 (10%) and 0.2- 0.3 (20%- 30%) under RCP8.5 and RCP4.5, respectively. Unlike finger millet, the spatial suitability of maize does not increase into areas that previously had no suitability. For the case of finger millet, the increase in suitability is greater under the RCP8.5 path than RCP4.5, whereby during the long rains, there is a projected increase in the suitability of around 0.5 (50%) in semi-arid counties namely Tana River and Garissa. However, throughout the rest of the country, the suitability of finger millet is projected to remain spatially very scattered.

Beans are grown during the long rain season, however, the historical suitability of common beans and broad bean has the highest suitability scores and widely spatial distribution in July, during the dry season for both RCPs. Suitability extends into several arid and semi-arid counties. The SIV of broad beans is seen to increase greatly in northeastern Kenya, within the driest counties in the country, such as Wajir and Mandera. By mid-century, during the dry season, the SIV of common bean and broad bean become suitable to excellent in the majority of counties in the country.

The historical suitability of sweet potato is very marginal and is only concentrated within central Kenya. During the long rains, sweet potato is very suitable in counties such as Bungoma and Busia, with marginal suitability in counties such as Nyeri and Kirinyaga. The projected change in suitability is minimal with a general reduction in SIV during the wet seasons (-40%) in areas that were historically marginally suitable. Future suitability projections remain very scattered.

Results from the soil pH analysis indicated the dominant role that climate has on overall suitability. This is evident for all 5 crops and especially true for finger millet. Finger millet has a pH tolerance threshold between 5 and 8, which equates to around 90% of the landmass in Kenya. However, the climate suitability was very scattered with low spatial distribution. The result of the overall climate and pH suitability, therefore, suggest that very few counties in western Kenya achieved suitable conditions to grow finger millet in April. For sweet potato, despite very small regions achieving the pH threshold and climate suitability, the majority of this area is considered as optimum suitability. Therefore, sweet potato has the potential to supplement staple crops within these regions in order to achieve better levels of food security.

6.2 Contribution of this study

This study contributes to the limited body of knowledge on orphan crops in Kenya. Results of this study indicate ways in which the state of food security within the country could improve through the integration of orphan crops into food systems. Methods of climate-smart agriculture, such as crop rotations or intercropping systems could incorporate orphan crops such as broad beans and sweet potato. This study provided evidence that future dry seasons could be used to plant broad beans. Therefore, a rotation between maize and broad bean, for example, could maintain more sustainable cropping systems in the future, such that the legume crop is able to restore nitrogen within the soil. Furthermore, such orphan crops can potentially reduce the pressure to produce maize that comes along with growing populations. Nonetheless, government support for infrastructure and services are essential to attain the diversification of food systems.

This study outlined the potential food security relief that the country can benefit from under the RCP4.5 in comparison to RCP8.5. Such evidence could steer governments and policy-makers to implement effective action in order to curb the emissions of GHGs, not only with the aim of reducing climate change but also as a means to avoid damaging impacts to the level of food security.

6.3 Recommendation for future studies

This study acknowledges the complexity of aiming for a more food secure country. Therefore, future studies could incorporate qualitative methods to assess the level of acceptance of climate change adaptation and mitigation. This study presents outcomes that suggest the diversification of cropping systems, with greater inclusion of orphan crops into the food systems to improve the state of food security. However, the success of such change would highly depend on the citizens' acceptance and willingness to bring the change. Age, income, education, gender and environmental beliefs are seen as important determinants to the acceptance of adaption and mitigation (Johnson & Nemet, 2010; Schwirplies, 2018). Such advances to this study would potentially provide valuable insights into the interrelation between citizens' attitudes, beliefs and environmental awareness of the implications of climate change on future crop suitability in Kenya.

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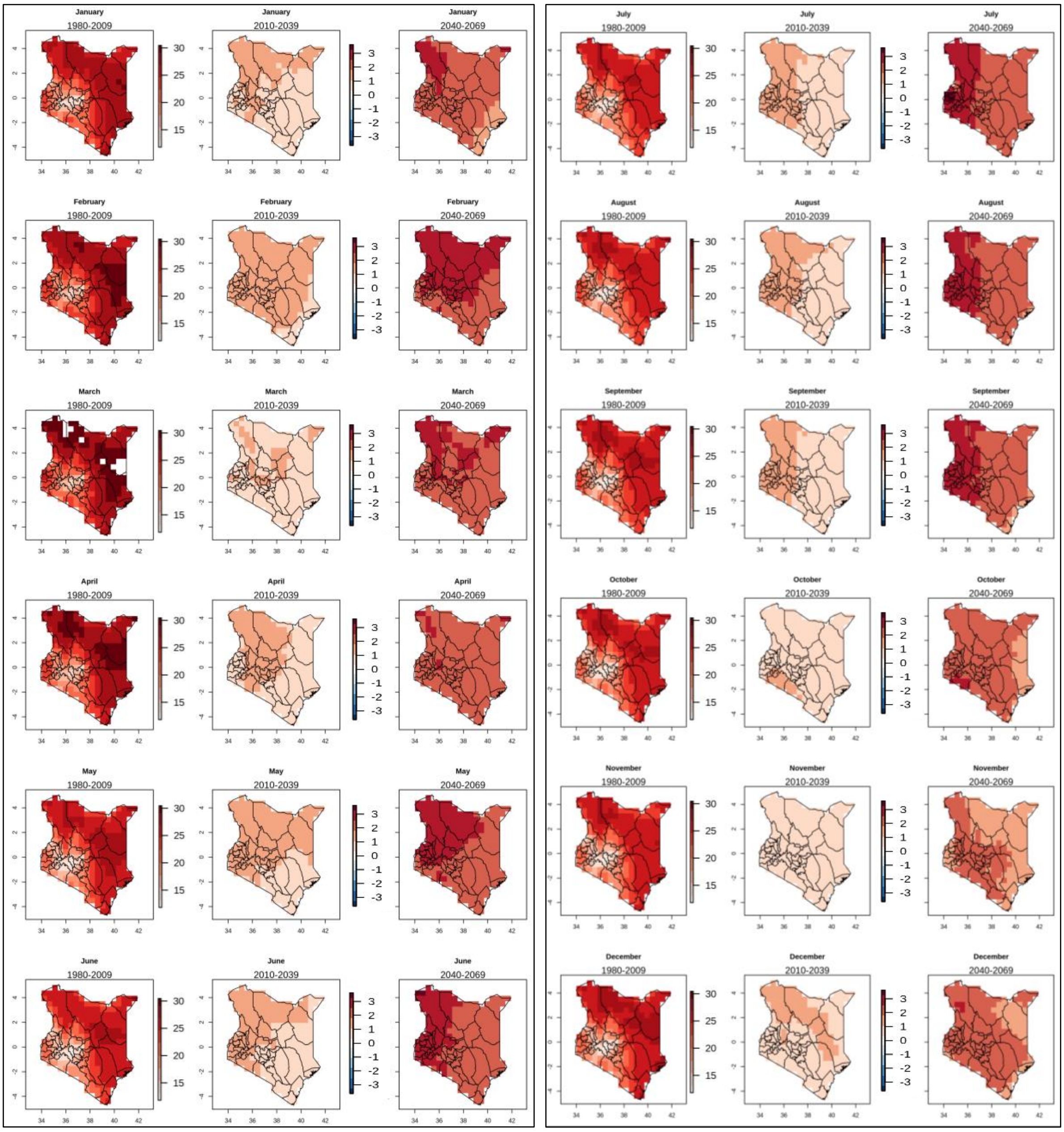
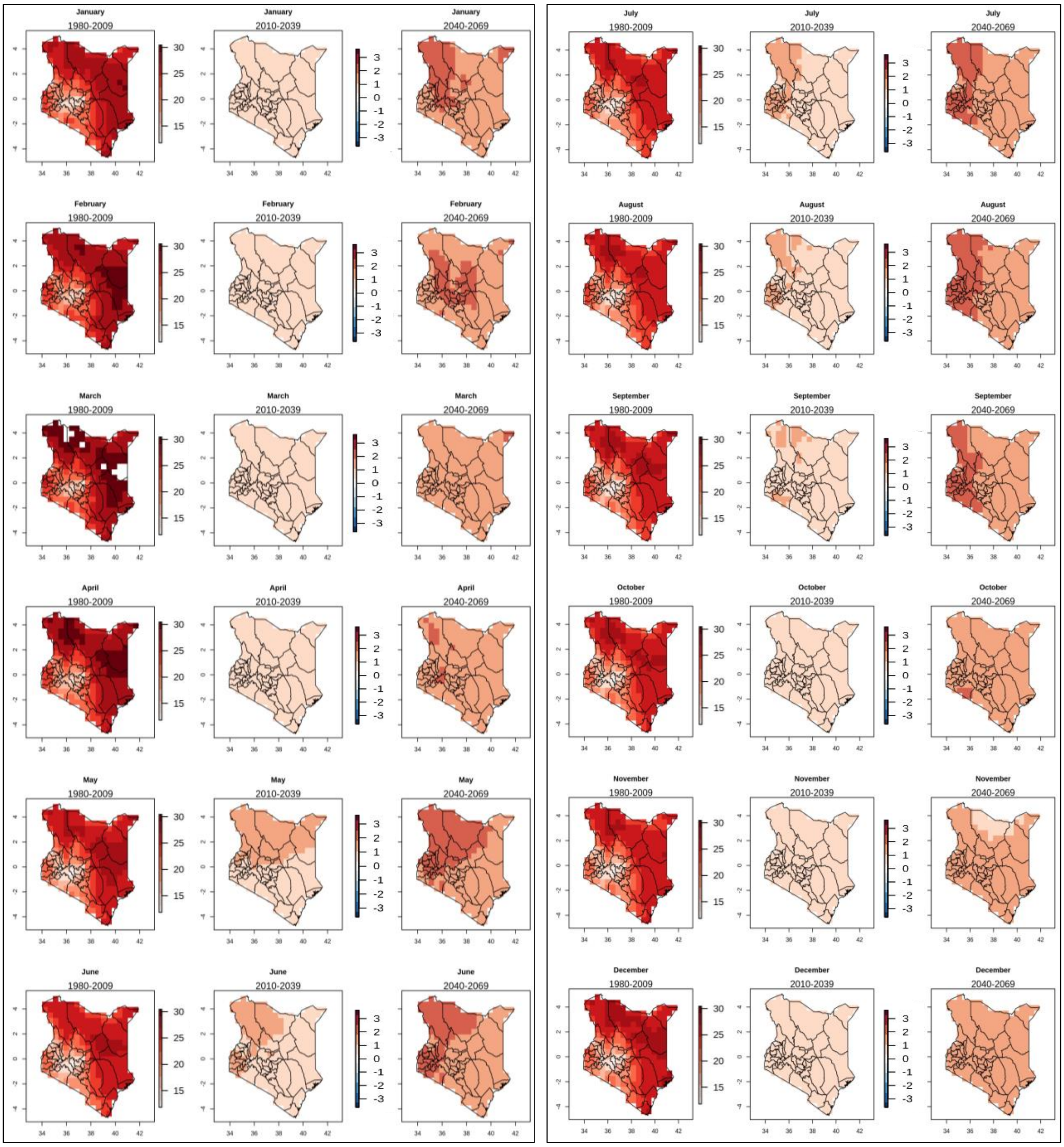
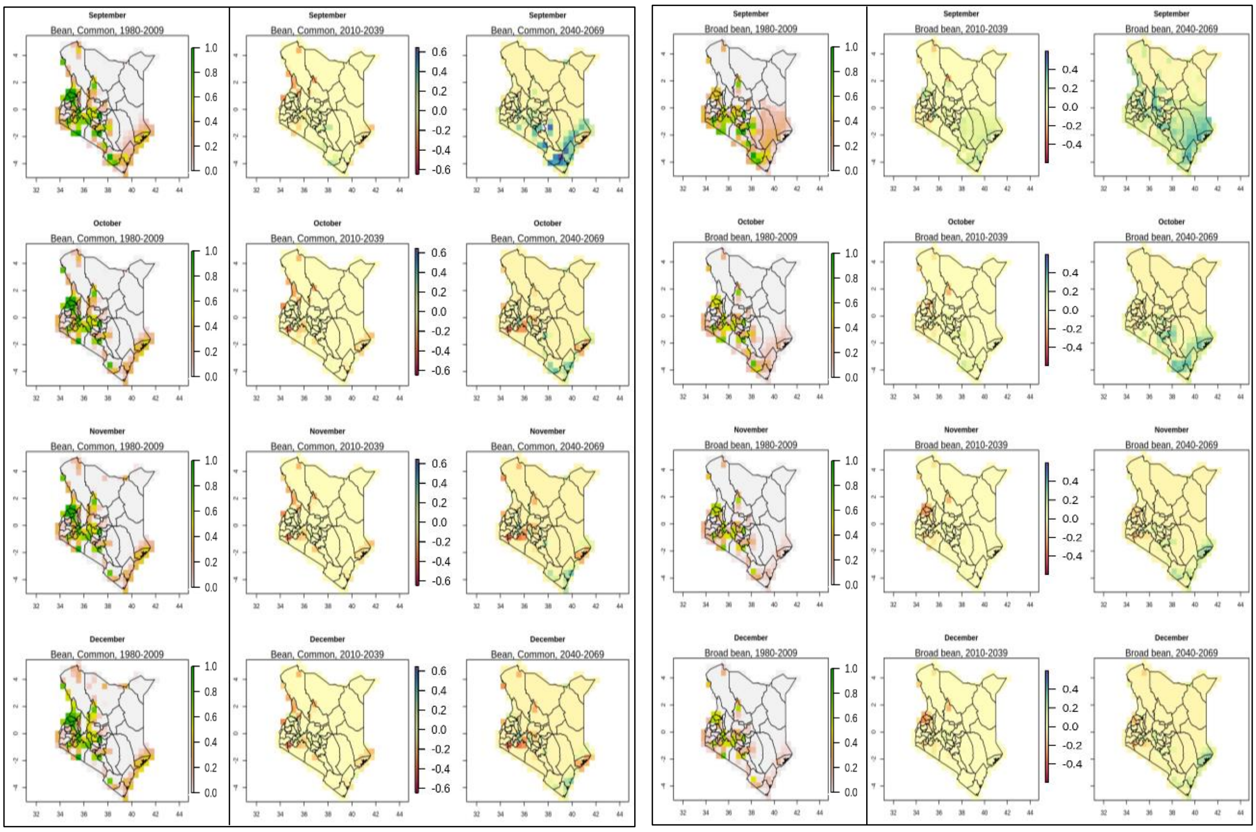
Appendix



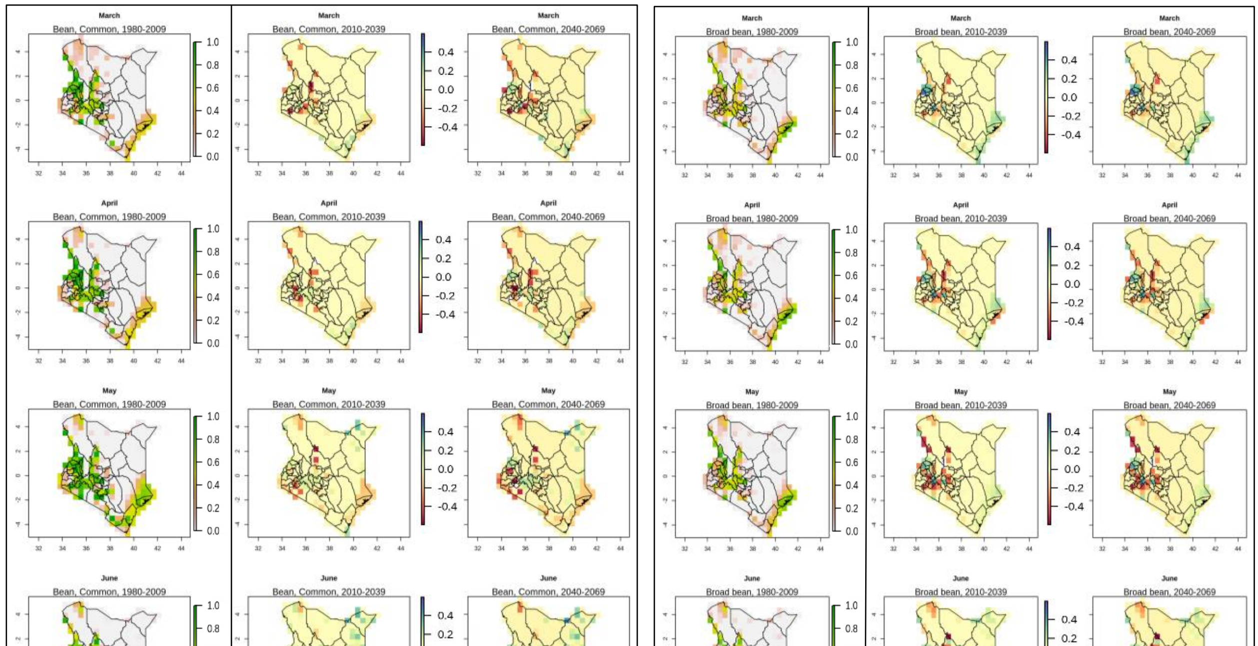
Appendix 1 Historical and projected changes in mean temperature (RCP8.5)



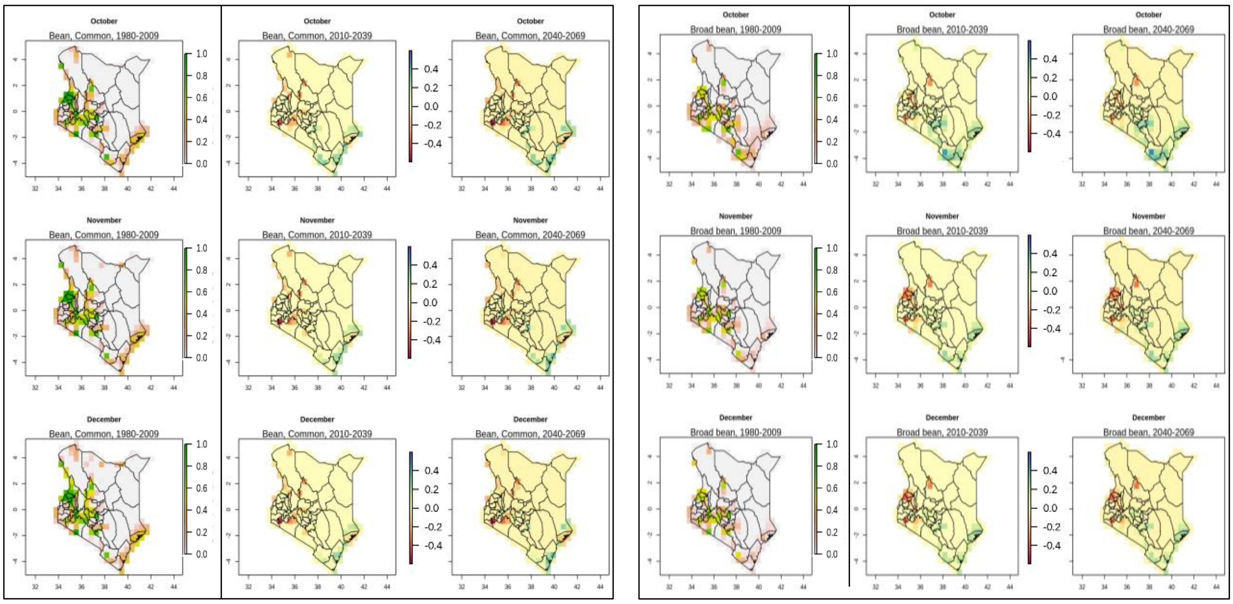
Appendix 2 Historical and projected changes in mean temperature (RCP4.5)



Appendix 3 Historical and projected change in suitability, during the short rains for RIGHT: Common bean and LEFT: Broad bean under RCP8.5



Appendix 4 Historical and projected change in suitability, during the long rains for RIGHT: Common bean and LEFT: Broad bean under RCP4.5



Appendix 5 Historical and projected change in suitability, during the short rains for RIGHT: Common bean and LEFT: Broad bean under RCP4.5