UNIVERSITY OF RWANDA

COLLEGE OF SCIENCE AND TECHNOLOGY

SCHOOL OF ARCHITECTURE AND BUILT ENVIRONMENT

MASTERS OF GEO-INFORMATION SCIENCE FOR ENVIRONMENT AND SUSTAINABLE DEVELOPMENT

Title of Project (Thesis)

Suitability analysis of coffee growing area in the Context of climate change in Nyaruguru District, Rwanda.

A thesis submitted in partial fulfillment for the degree of Master of Geo-Information Science for Environment and Sustainable development in the School of Architecture and built environment, College of Science and Technology, University of Rwanda.

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October, 2018

DECLARATION

I hereby declare that the study “**Suitability analysis of coffee growing area in the Context of climate change in Nyaruguru District, Rwanda**” is my original work and has never been submitted for a degree award in any other university.

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Dedication

This work is dedicated

To

My family and Friends for their encouragement and unconditional support.

ACKNOWLEDGEMENT

This research would not have been successfully completed without support from different persons. That is why I would like to express my gratefulness to those who made everything happen in a good way.

My foremost thanks go to the Almighty God for His priceless mercy and grace and guidance throughout my life and the strength to complete this study.

Sincere appreciations are addressed to my supervisors Theophile Niyonzima (PhD) from the University of Rwanda and Nicole Ueberschär (PhD) from ESRI Rwanda for their direction, constructive comments and important advice. In addition, my gratitude goes to Paul Watkiss for inspiring and supporting this research, and Solange Uwera for her guidance and support.

Furthermore, my credits are addressed to all classmates, for making the class a pleasant and enjoyable place for academic learning, sharing ideas and scientific discussions, for their cooperation and team spirit.

Finally, may God bless all persons who directly or indirectly contributed to the accomplishment of this study; my brothers and sister, and Solange Impanoyimana.

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LIST OF ABBREVIATIONS AND ACRONYMS

AHR	: Analytical Hierarchical Process
AR5	: Fifth Assessment Report
CBD	: Coffee Berry Disease
DEM	: Digital Elevation Model
DTM	: Digital Terrain Model
FY	: Fiscal Year
GDP	: Gross Domestic Product
GIS	: Geographic Information System
GIS-MCDA	: GIS multi-criteria decision-making analysis
IPCC	: Intergovernmental Panel on Climate Change
MINAGRI	: Ministry of Agriculture and Animal Resources
MT	: Million Tone
NAEB	: National Agricultural Export Development Board
NISR	: National Institute of Statistics Rwanda
pH	: Potential Hydrogen
PRISM	: Parameter-elevation Regressions on Independent Slopes Model
RAB	: Rwanda Agriculture Board
RCP	: Representative Concentration Pathways
REMA	: Rwanda Environment Management Authority
UNFCCC	: United Nations Framework Convention on Climate Change
USAID	: United States Agency for International Development
WGII	: Working Group II Contribution to the Fifth Assessment Report
WGS 1984	: World Geodetic System1984
CSAG CIP	: Climate System Analysis Group's Climate Information Portal

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ABSTRACT

Coffee is a top export commodity and an important source of revenue for Rwandan economy contributing to about 33 % of gross domestic product of the country. Unfortunately, the changing climate and climate variability poses a great threat to the growing sector. Rwanda in general and rural areas specifically are threatened by the changing climate due to poverty and high population. With about three quarters of the Rwandan population relying on agriculture, suitability analysis for coffee has to be conducted to inform decision makers, development partners and famers on possible alternatives for adaptation mostly in rural areas. In this study, Suitability analysis of coffee growing area in the context of climate change in Nyaruguru District, Rwanda, a combination of GIS and spatial statistics methodology were used.

We used a geographic information system (GIS) for a weighted overlay analysis to produce Arabica Coffee suitability map. The Elevationally Detrended Ordinary Kriging and the Inverse Distance Interpolation technics were used together with Multiple-criteria decision analysis to produce suitability maps. Hence, the results show that the projected temperature and precipitation for over 30 years from 2016 will increase between 1.3°C and 2.25°C considering both RCP4.5 and RCP8.5 scenarios. Thus, this increase will lead the temperature beyond optimum Arabica coffee growing condition of 22°C in the large part of the district area in next 30 years. The 2016 suitability map shows that 77.6% of Nyaruguru is suitable and 4% is highly suitable while about 17.9% of Nyaruguru district which is unsuitable is part of Nyungwe National Park where precipitation is the limiting factor. The results suggest that progressive coffee extension to more suitable areas and smart agriculture practices such as contour farming should be taken into consideration by the government and development partners, and smallholder famers respectively to avoid the loss of yield and good quality in coming years.

Key Words: *Suitability analysis, climate change, Arabica Coffee, climatic conditions, temperature, and precipitation.*

CHAPTER 1: INTRODUCTION

1.1. Background

The Rwandan economy is based mainly on agriculture (IPAR, 2009). This sector is crucial for Rwanda's growth and reduction of poverty, as the backbone of the economy. It accounts for 33 % of Gross Domestic Product (GDP) (NISR, 2016), employs 80 % of the workforce and provides raw materials to industries and a market for manufactured goods (Bizimana *et al.*, 2012). The country's average annual income of $550 per capita reflects a rural poverty rate of 49 % that soars to 76 % for families whose main source of income is agriculture (World Bank, 2013).

However, the agriculture is one of the sectors most affected by ongoing climate change (De Salvo *et al.*, 2013). The strong trends in climate change already evident, the likelihood of further changes occurring, and the increasing scale of potential climate impacts give urgency to addressing agricultural adaptation more coherently (Howden *et al.*, 2007). Developing countries rely heavily on climate-dependent agriculture and especially in conjunction with poverty and rapid increase in population, they are vulnerable to climate change (Porter *et al*., 2014).

Agriculture in its many different forms and locations remains highly sensitive to climate variations (Howden *et al.*, 2007). Thus, climate change is expected to substantially reduce agricultural yields (Shi and Tao, 2014), as reported by the Intergovernmental Panel on Climate Change (Porter *et al.*, 2014). The agricultural sector will face serious challenges in the coming decades due to the sensitivity of crops to water shortages and heat stress (Ramirez-Villegas, 2012) and some countries are already experiencing them (Ali *et al*., 2017).

In Rwanda, the agricultural exports represent over 70 % of the total value of exports. Coffee and tea are the two main export crops and the most widely cultivated and most important cash crops in Rwanda (Bizimana *et al.*, 2012, Hakorimana and Akcaoz, 2017). In the coffee value chain, the 2014-2015 fiscal year registered a production of 16,924 MT and exports of 16,529 MT that generated an export revenue of 64.02 Million USD (NAEB, 2014). It also provides livelihoods for many small-holder farmers. However, while the land area for cultivation of coffee (and tea) has been increasing in recent years, production volumes do not demonstrate a clearly increasing trend. This implies varying yield productivity and other potentially climate-related influence factors (GIZ, 2014).

Rwanda produces mainly Arabica coffee; 97 % of Rwanda's coffee cultivation is Arabica (Hakorimana and Akcaoz, 2017), largely cultivated by smallholder farmers as mono-crop on plots of less than a hectare scattered on hilly slopes (Nzeyimana *et al.*,2014). Rwanda is more suitable for Arabica variety due to its climate and geographic location. The growing conditions for Arabica coffee in Rwanda are characterized by an altitude of at least 1000 m a.s.l. (Ovalle-Rivera *et al.*, 2015), annual precipitation of between 1400 and 2000 mm, temperatures of 18°C – 22°C, and an average amount of sunlight of 2200–2400 hours per year (Verdoodt and Ranst, 2003). Arabica coffee also requires sandy loam soil with a moderately coarse texture dominated sandy soil concentration of 50%-70% (Barham *et al.*, 2006), a pH of 4.5–6.0, moderate to high sums of basic cations, and 2–5% organic matter (Verdoodt and Ranst, 2003).

Foods producing crops and industrial crops mainly coffee(and tea) have a very high degree of sensitivity to climatic stressors, especially during seasons of frequent and prolonged droughts as well as heavy or poor rains (GoR, 2006). Thus, coffee is vulnerable to high temperature increases and decreases, and a specific precipitation range depending on the varieties (Choudhary *et al.*, 2015). This implies the deviations outside the aforementioned range, the amount of precipitation that it is sensitive to, the frequency and distribution. This existing sensitivity explains why a changing climate will have subsequent impact on agriculture (Howden *et al.*, 2007) in general and on coffee specifically as it is very sensitive.

In fact, it is predicted that rising temperatures and water shortages will negatively affect coffee production suitability at lower elevations and vice versa (Bongase, 2017). Model-based predictions of future greenhouse gas-induced climate change for the continent clearly suggest that this warming will continue and, in most scenarios, accelerate so that the continent on average could be between 2 and 6°C warmer in 100 year time (Hulme *et al.,* 2001). In this scenario, coffee production is also likely to decrease globally, particularly in Africa (Bongase, 2017). The predicted changes in coffee suitability are directly linked to latitude. Higher temperatures would cause areas growing Arabica coffee within 5°–10° of the equator at elevations less than 1000 m a.s.l. to lose climatic suitability. Changes in annual precipitation and its seasonality would have little effect (Ovalle-Rivera *et al.*, 2015).

1.2. Problem statement

Coffee has proven to be highly sensitive to climate change (Bunn *et al.,* 2015). According to various studies (Alexandratos and Bruinsma, 2012, Thornton *et al*., 2009, and Sachs *et al*., 2015), nearly 20 countries could lose all naturally highly suitable coffee land due to climate change. Globally, suitable regions may decrease by 56% (Sachs *et al*., 2015) even the exact amount is not certain. This is due to the fact that coffee has a restricted and specific climatic and environmental suitability that determine its distribution. Data for cultivated Arabica confirms these observations, and shows that this species is sensitive to climate variables, particularly temperature and precipitation (Davis *et al.*, 2012).

Temperature and precipitation conditions are considered to be important factors in defining potential coffee yield (Haggar and Schepp, 2012). Temperature is one of the most critical environmental factors and exerts a great influence in all the physiological activities of plants, controlling the levels of the metabolic reactions within cells (Alves and Mazzafera, 2008). Both factors interfere in the crop phenology, and consequently in productivity and quality (Haggar and Schepp, 2012). In addition to that, soil also plays an important role in determining coffee suitability. In addition to that, Nzeyimana *et al.* (2014), concluded that the spatial variation of coffee productivity in the agro-ecological zones was considerable and was influenced by soil properties, soil management, farming practices, and climatic conditions. Where climatic conditions are optimal or near optimal, these soil properties will determine the spatial distribution of the final suitability. However, important deviations from this general rule have been reported for crops such as Arabica coffee that is very demanding (Ann Verdoodt and Ranst, 2006).

The climate of Rwanda is already changing (MINIRENA, 2017). Despite that the government of Rwanda has strategic plans to transform the agricultural sector, it was found that the extreme events such as flooding and droughts from current variability, as well as future climate change, pose a major risk to agricultural sector growth and the sector development targets (Hunt, Watkiss, and Mullen, 2011). Moreover, climate change is likely to have far greater effects on the small farmers compared to the larger commercial operations (FAO, 2008) and the coffee sector in Rwanda, which is dominated by small scale farmers(Guariso *et al.*,2012) is more exposed to the impacts and effects of climate change.

Regional studies have shown that changing climate will affect climatic suitability for Arabica coffee within current regions of production (Ovalle-Rivera *et al.*, 2015). However, coffee varieties are affected differently and some are more suitable in a specific area than others. The GIS based suitability analysis for coffee farming conducted in Kenya in 2015 revealed that farmers need to consider growing more of Arabica coffee and less of the Robusta type (Rono and Mundia, 2016) due to its suitability.

In Rwanda, apart from a Large-Scale Land Suitability Classification for Rwanda (Verdoodt and Ranst, 2003) and a GIS-Based Multi-Criteria Analysis for Arabica Coffee Expansion in Rwanda (Nzeyimana *et al.*,2014), there is a big gap in suitability analysis of coffee growing area in Rwanda mostly in the context of climate change while studies confirmed the relevance of climatic conditions in determining coffee suitability (Ann Verdoodt and Ranst, 2006).

In fact, the first global study on the impact of climate change on suitability to grow Arabica coffee was conducted in 2014 (Ovalle-Rivera *et al.*, 2015) and no similar studies were conducted in Rwanda up to date. Thus, with 98% of all the coffee produced in Rwanda (Guariso *et al.*, 2012) being Arabica variety, the sector is very critical and coffee suitability analysis of coffee growing areas have to be undertaken to inform planners, decision makers, and mostly the farmers in the context of this changing climate.

The GIS-Based Multi-Criteria Analysis for Arabica Coffee Expansion in Rwanda analyzed suitable areas for Arabica coffee production with a focus on the spatial distribution of actual and potential production zones for Arabica coffee, their productivity levels and predicted potential yields (Nzeyimana*et al.*, 2014). The here presented study will build on their work in the context of climate change with a focus on how the projected climate change is likely to affect the suitability of coffee growing areas in Nyaruguru district of Rwanda.

Nyaruguru district is one among coffee growing areas in Rwanda with 175 MT fully washed coffee as of 2015/2016 fiscal year. In addition to the already changing climate of Rwanda, the land constraints due to high population pressure, poor water management, small average land holdings, lack of public and private capacity, and limited commercialization constrained by poor access to output and financial markets, pose challenges to coffee sector growth in Nyaruguru district (MINIRENA, 2017). Thus, the suitability analysis of Coffee growing area in the context of climate change in Nyaruguru will contribute in addressing some of those challenges listed mostly those related in planning and sector growth. In fact, Nyaruguru district is among the districts that have a high percentage of cultivating households (87%) under 0.9 ha of land. Moreover, it is among the districts with a high percentage of extreme-poor and poor population categories: 35.4% are extremely poor and 26.2% poor (excluding extreme-poor) (NISR, 2011).

Therefore, planners, decision makers, and coffee farmers have to be informed on the potential coffee growing areas in the context of climate change so that the policies and investments should promote and be chained in coffee extension programs respectively in identified coffee cultivation suitable areas. This will ensure smooth transition over years without affecting the economy of the country and the life of thousands of coffee farmers who depend on incomes generated from coffee farming.

There is still room for research on coffee suitability to enrich governmental and development partners' priorities in rural areas like Nyaruguru district. This research will inform the new policies and master plans so that future district plans and strategies should take into consideration coffee suitability due to the irreversible role of agricultural and coffee specifically in the development of Nyaruguru district and the country in general.

1.3. Research objectives

The main goal of this study is to conduct the suitability analysis of coffee growing area in the context of climate change in Nyaruguru District, Rwanda. The specific objectives of this study are (i) to analyze monthly climatic projected data for over 30 years, (ii) to examine the impact of environmental factors on coffee distribution in Nyaruguru district, and (iii) to assess possible adaptation measures for smallholder famers in the context of climate change.

1.4. Research questions

This study is conducted on Nyaruguru district and it is guided by the following research questions: (1) Will temperature and precipitation increase or decrease in coming 30 years? (2)

What is the current suitable areas to grow coffee in Nyaruguru district based on current data? (3) What adaptation measure should be taken to tackle negative impact of climate change on coffee sector in Rwanda based on Nyaruguru district case study?

1.5. Significance of the study

The future climate change poses a major risk to coffee sector in Rwanda; the change in climatic conditions and extreme events could have large impacts on both productivity and quality of coffee that attracts many buyers. Thus, the Suitability analysis of coffee growing area in the Context of climate change in Nyaruguru District, Rwanda comes at the right moment when the country is facing many extreme events attributed to climate change and planers are elaborating strategies and policies to address this issue.

This study is very important because it will help planers, decision makers, small holder farmers, development agencies and concerned ministries in general to plan ahead for coffee adaptation to climate change and coffee expansion in the region where it will be more suitable and productive in coming decades. This research will be the first of its kind conducted on coffee sector in Nyaruguru district, one among fertile coffee growing area in Rwanda with more than 375 MT production of fully washed coffee.

At larger scale, this research is relevant for the nation, development agencies, districts planners, and small holder farmers as Rwanda is working to increase its resilience towards the changing climate while ensuring sustainable development. This study provides relevant information to different stakeholders in coffee sector in Rwanda. The results from this study will be availed and shared with all stakeholders in coffee sector in Rwanda and in the region to give them the information that they can use to improve and promote the wellbeing of small holder farmers mostly those in coffee sector in rural areas.

1.6. Limitation of the study

While conducting this study, some limitations were encountered. Firstly, the availability of recent and accurate data was the main issue faced mostly for Nyaruguru district, the study area. The whole Nyaruguru district has only five meteorological stations that don’t have records for past years. Secondly, the projected data used were representative not absolute. Thus, monthly temperature and precipitation projection were produced.

1.7. Delimitation of the study

This study was conducted on Nyaruguru district and focused mainly on climatic factors, temperature and precipitation, as they play an important role on coffee growth. Thus, the monthly temperature and precipitation for the past 30 years from 2016 was assessed and then compared to 2016 records and 30 years' projection data to assess the trends and variation. Moreover, the pH and sandy soil concertation are assessed. To produce the final suitability map, climatic, soil and topographic conditions are modelled. For temperature projection data, the Representative Concentration Pathways (RCPs) 4.5 and 8.5 scenarios were considered.

CHAPTER 2: LITERATURE REVIEW

2.1. Agriculture sector and climate change

Climate change has emerged in recent years as one of the most critical topics (Bongase, 2017) and it has become an internationally recognized problem (Fischersworring *et al.,* 2015). Hence, the term climate change as defined by the Intergovernmental Panel on Climate Change (IPCC) "refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer" (IPCC, 2007b). It refers to any change in climate over time, whether due to natural variability or as a result of human activity. On the other side, this usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where "climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and [that] is in addition to natural climate variability observed over comparable time periods" (United Nations, 1992)

Climate change will have critical impacts on the economies of the region and threatens to reverse the gains of sustainable development in Africa (Madzwamuse, 2011). "The speed of the current climate change is faster than most of the past events, making it more difficult for human societies and the natural world to adapt" (The Royal Society & National Academy of Sciences, 2014). By 2020, according to the IPCC 2007, between 75 and 250 million people are projected to be exposed to increased water stress due to climate change. Climate-change impacts are expected to exacerbate poverty in most developing countries and create new poverty pockets in countries with increasing inequality, in both developed and developing countries (IPCC, 2014). In fact, Climate change is an additional stressor for a continent that is already struggling with food insecurity, high poverty levels, and a HIV/Aids pandemic (Madzwamuse, 2011). Hence, in some countries, yields from rain-fed agriculture could be reduced by up to 50%. Agricultural production, including access to food, in many African countries is projected to be severely compromised. This would further adversely affect food security and exacerbate malnutrition (IPCC, 2007).

Regional studies have shown that climate change will affect climatic suitability for Arabica coffee within current regions of production (Ovalle-Rivera *et al.,* 2015). In fact, coffee in general requires very specific growing conditions that determine the growing area, yield and quality.

Coffee is particularly sensitive to changes in seasonal temperatures and precipitation. In the regional, the optimum temperature ranges between 15°C and 24°C; precipitation between 1500 mm and 2000 mm per annum and is typically cultivated at altitudes between 1000 and 2000 m a.s.l. (Killeen and Harper, 2016). The growth of Arabica coffee declines significantly if the daytime temperature is below 18° C (Alemu and Dufera, 2017) or exceeds 23° C (DaMatta, 2004). Indeed, if temperature and precipitation are not ideal at the flowering season (are too cold or too wet), many difficulties may be encountered (Bittenbender & Smith, 2008).

Any increase in temperature and changes in precipitation patterns will decrease yield, reduce quality and increase pest and disease pressure (Ovalle-Rivera *et al.,* 2015).The Arabica coffee variety is susceptible to disease due to its highly sensitivity (Naveen *et al.,*2010). It is worth noting that increased temperature doesn't make the plants more sensitive to pests and diseases but rather makes the occurrence of pests and diseases more common, which then impact the plant. The higher temperatures make the coffee more susceptible to disease, and favor pests such as leaf miners, stem borers and certain nematodes, which multiply more rapidly under these conditions (GIZ, 2011). Thus, temperatures above 25°C affect the plant's photosynthesis process and spur the development of diseases such as coffee leaf rust (CLR) and fruit blight. Low temperatures, below 15°C, spur coffee berry disease (CBD) (Ngabitsinze *et al.,* 2011). Therefore, an increase in temperature and changes in precipitation patterns will tend to decrease yield, reduce quality and increase pest and disease pressure (Ovalle-Rivera *et al.,* 2015) if no counteractive management practices are implemented, like irrigation. Furthermore, according to the Fifth Assessment Report by the IPCC Working Group II, highland Arabica coffee producing areas are at risk to see an increase in the coffee berry borer (*Hypothenemus hampei*) through warming temperatures.

In fact, the continent of Africa is warmer than it was 100 years ago (Hulme *et al*., 2001). In East Africa, climates suitable for Arabica coffee are predicted to shift from 400–2000 m a.s.l. to 800–2500 m a.s.l. making little change in suitability of the areas in Ethiopia, Kenya, Rwanda, and Burundi that currently grow Arabica (Ovalle-Rivera *et al.,* 2015). Coffee supply chains are likely to experience significant disruption due to climate change over the next forty years (Killeen and Harper, 2016). By 2050s, it is predicted that global temperatures would increase by 2°C together with some increased seasonality of precipitation. These changes would reduce climatic suitability for Arabica coffee at low elevations and increase suitability of higher areas. The net effect is that coffee farming will tend to move uphill (Ovalle-Rivera *et al.*,2015).

In fact, Rwanda has placed the transformation of the agricultural sector at the center of its development agenda (Guariso *et al.,* 2012). Although, Rwanda has one of the lowest emissions per capita in the world, estimated at 0.4 tCO2e/person, compared to a global average of 6.7 tCO2e/person, as according to Rwanda's second national communication to the UNFCCC (GoR, 2012), it is highly vulnerable to the impacts of temperature and precipitation changes due to climate change since it relies heavily on rain-fed agriculture for subsistence livelihoods and tea and coffee cash crops (REMA, 2009). Coffee (and tea) are important cash crops in Rwanda (Verdoodt and Ranst, 2003). Despite its tangible role in the development of the country and controlling its economy, coffee supply chains are likely to experience significant disruption due to climate change over the next forty years (Killeen and Harper, 2016).

Increasingly, the research community has turned their interest on the effect of climate change on the agricultural sector. Climate change has emerged as the most prominent of the global environment issues and there is a need to evaluate its impact on agriculture (Naveen *et al.,* 2010). The concern over the potential effects of long-term climatic change on agriculture has motivated a substantial body of research over the past decade. In fact, "climate is the primary determinant of agricultural productivity" (Res *et al.,* 1998). Thus, there is widespread interest in the impacts of climate change on agriculture in Sub-Saharan Africa (Schlenker and Lobell, 2010) even if robust analyses of coffee and climate change at the regional scale have until now been lacking (Craparo *et al.*, 2015).

There is no doubt that climate change is happening in Rwanda; the recent extreme events and the climate change profile of Rwanda (GoR, 2015) clearly indicate that current trends in precipitation and temperature are expected to continue in the future. Observations indicate a rise in average annual temperatures of about 0.7°C - 0.9°C since 1950 (USAID, 2011) and an increase of about 0.35°C per decade slightly higher than the observed global average of 0.27°C per decade from 1979 to 2005 (IPCC, 2007a). The analysis of number of days of rainy seasons shows a progressive tendency of short rainy seasons (GoR, 2006). The monthly average precipitation totals, generally decreased in the last years (1991-2009 period) and heavy daily precipitation is becoming more and more quantitatively significant (EAC, 2011). Moreover, extreme events associated with El Niño and La Niña episodes have intensified; droughts in eastern and southern regions have resulted in a series of severe famines and heavy precipitation in northern and western regions has led to erosion, flooding, and landslides (USAID, 2011).

2.2 Impact of climate change on coffee production

Recently, various studies went deep to understand the impact of climate change on coffee sector as environmental factors mainly temperature and rain are indispensable for plant growth. Bunn et al. (2015) concluded in their paper that coffee has proven to be highly sensitive to climate change. Temperature and precipitation conditions are considered to be important factors in defining potential coffee yield (Haggar and Schepp, 2012). Hence, it was proved that coffee is sensitive to climate and the temperatures are already causing shifts *(Sachs et al.*, 2015). The regional studies have shown that climate change will affect climatic suitability for Arabica coffee within current regions of production (Ovalle-Rivera *et al.*, 2015). Thus, the temperature across the coffee belt is expected to rise by 2.1°C by 2050 and the precipitation across the coffee belt is expected to increase by 1.7% (Sachs *et al.*, 2015) making the region less suitable for coffee or causing shifts in other place. However, precipitation changes are difficult to model and unreliable, in some places precipitation will decline more, in other it will increase. This will have a big impact on coffee productivity and distribution across the world and mostly in the region. With higher temperatures in the future, crop pests could expand their ranges but so could coffee and tea crops, among other potential impacts (REMA, 2009).

2.3. The optimum climatic condition for Arabica coffee

The optimum mean annual temperature range for Arabica coffee is 18°–21°C (DaMatta, 2004) while the optimum precipitation for Arabica cultivation range from 1200-2000mm well-distributed (Kuit *et al.*, 2004). According to Haggar and Schepp (2012), the temperature and precipitation conditions are considered to be important factors in defining potential coffee yield. Both factors interfere in the crop phenology, and consequently in productivity and quality. Therefore, increases in temperature and changes in precipitation patterns will decrease yield, reduce quality and increase pest and disease pressure (Ovalle-Rivera *et al.*, 2015). It will also have a great impact in shifting current coffee growing areas. In fact, Arabica coffee is grown at high elevations, in warm regions, with sensitive quality, and multiple positive and negative ecosystem interactions. The existing coffee plantations may thus experience the climate change foreseen by Global Circulation Models (GCMs) (Bunn *et al*., 2015).

2.4. The optimum soil condition for Arabica coffee

The Arabica coffee has specific soil requirements, although it can perform well on different types of soil (Kuit *et al*., 2004) and sandy loam soil is ideal for growing Arabica (Winston *et al.*, 2005). Based on the guidelines for soil description (Barham *et al*., 2006), sandy loam has a moderately coarse texture dominated by sandy soil concentration 50%-70%. On the other side, the ideal pH for Arabica species growth should be between 4.5 to 6 (Kuit *et al*., 2004) even if the coffee plant can still grow around neutrality (DAFF, 2012). In fact, few soil test results exist, low pH will limit crop performance by upsetting the availability of key nutrients to coffee plants (Winston *et al.,* 2005).

2.5. The optimum topographic condition for Arabica coffee

Arabica coffee requires an elevation between 1,200 and 2,200 m above sea level at the equator, but the optimal altitude can be less at higher latitudes (Pohlan, 2009). Thus, low elevation Arabica coffee does not possess the quality required by the world markets (Michon, 2015). On the other side, flat to 5% sloped coffee plantation is ideal growing condition and the contour should be applied on slopes above 5% (Kuit *et.*, 2004). In fact, the sloped plantations expose coffee plantation to sunny light. The light intensity depends on shade trees and it also depends on the exposure of the slope on which coffee trees are grown (Avelino *et al.*, 2005). However, the productivity of coffee plants grown on steep slopes quickly declines as fertile topsoil is lost (Iijima *et al.*, 2003) but the way slope exposure affects coffee quality has yet to be studied (Avelino *et al.*, 2005).

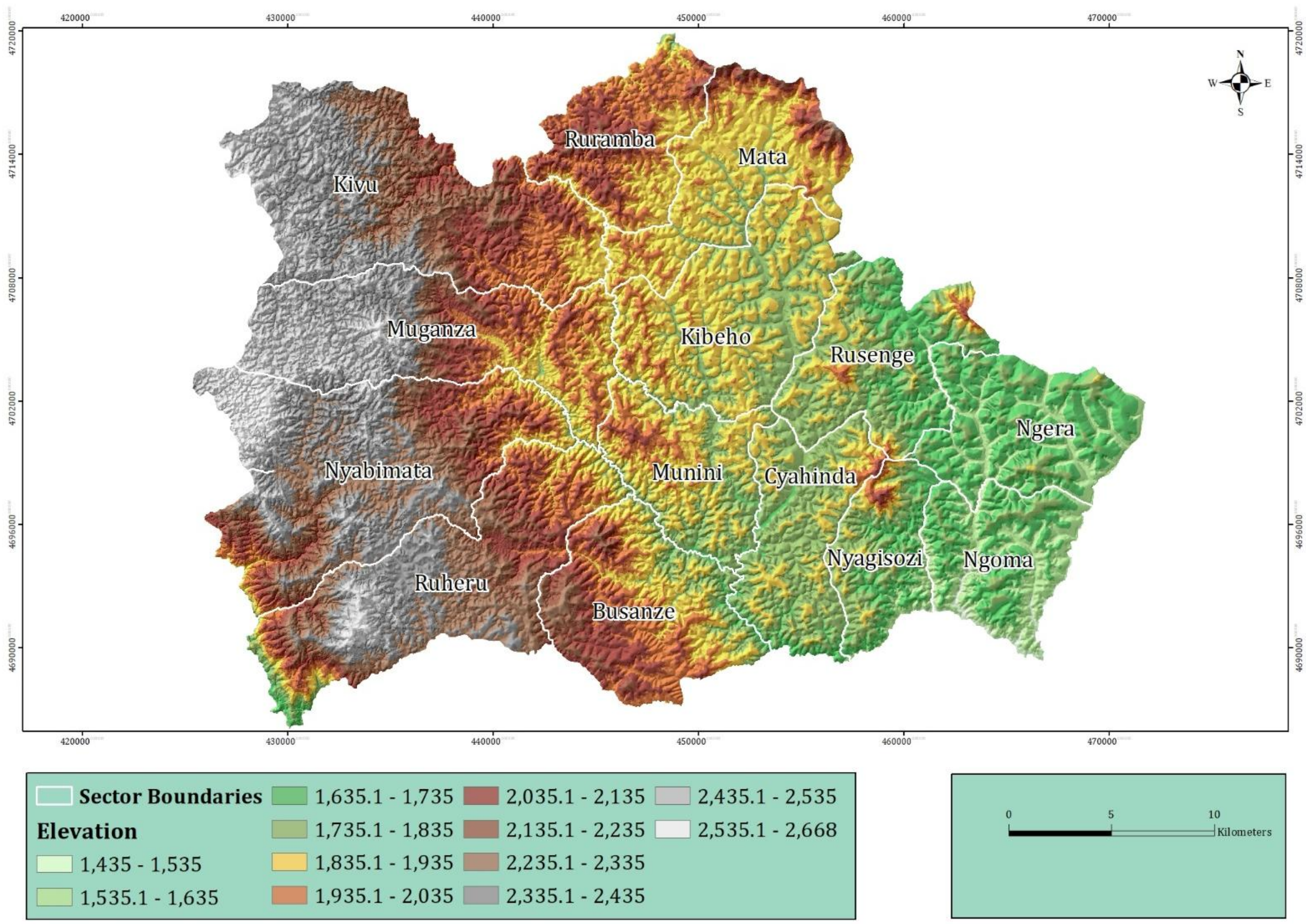
CHAPTER 3: METHODOLOGY

This chapter gives detailed information about the data used and the methodological framework followed during data analysis. First, an overview on the study area is given. Second, data acquisition and datasets used is explained in detail. Finally, data processing and analysis are explained with a focus on used approaches and spatial statistic technics. This study examines the main driving factors affecting coffee growth such as temperature and precipitation. Elevationally Detrended Ordinary Kriging methodology was used for temperature while Inverse Distance Interpolation was used for precipitation. Those technics were used to produce maps while Climate Reanalyzer was used to predict temperature and precipitation in coming 30 years.

The analytic hierarchy process (AHP) method of Multi-criteria analysis (MCA) developed by Thomas L. Saaty in the 1970 was used in the suitability analysis of coffee growing area in Nyaruguru district in the context of climate change. In fact, the Analytic Hierarchy Process is a theory of measurement through pairwise comparisons and relies on the judgements of experts to derive priority scales (Thomas 2008). Thus, climatic, topography, and soil conditions were weighted based on the literature review where climatic conditions weight more than other factors. The process of carrying out a comprehensive coffee suitability analysis requires a consideration of a number of criteria (Rono & Mundia, 2016). It enables the integration of different data layers with different levels of uncertainty (Feizizadeh & Blaschke, 2013) that are often evaluated by a number of individuals (decision-makers, managers, stakeholders, interest groups) (Malczewski, 2006).

3.1. Description of the Study area

This study is conducted in Nyaruguru district. Its location stretches out between 2°30' latitude South and 29°20' to 29°40' longitude East. Nyaruguru district is one of 30 districts in Rwanda and it is located in Southern Province. It covers an area of about 1010 km^2 and borders the Republic of Burundi in the South, Nyamagabe and Huye districts in the North, Rusizi district from Western Province in the West, and Gisagara district in the East. It is composed of 14 Sectors, 72 Cells and 332 Villages. The population of the District is 294,334 with 155,055 women and 139,279 men included in 61,143 household (NISR, 2015). Nyaruguru district is among the districts that have a high percentage of cultivating households (87%) cultivating each under 0.9 ha of land (NISR, 2011).

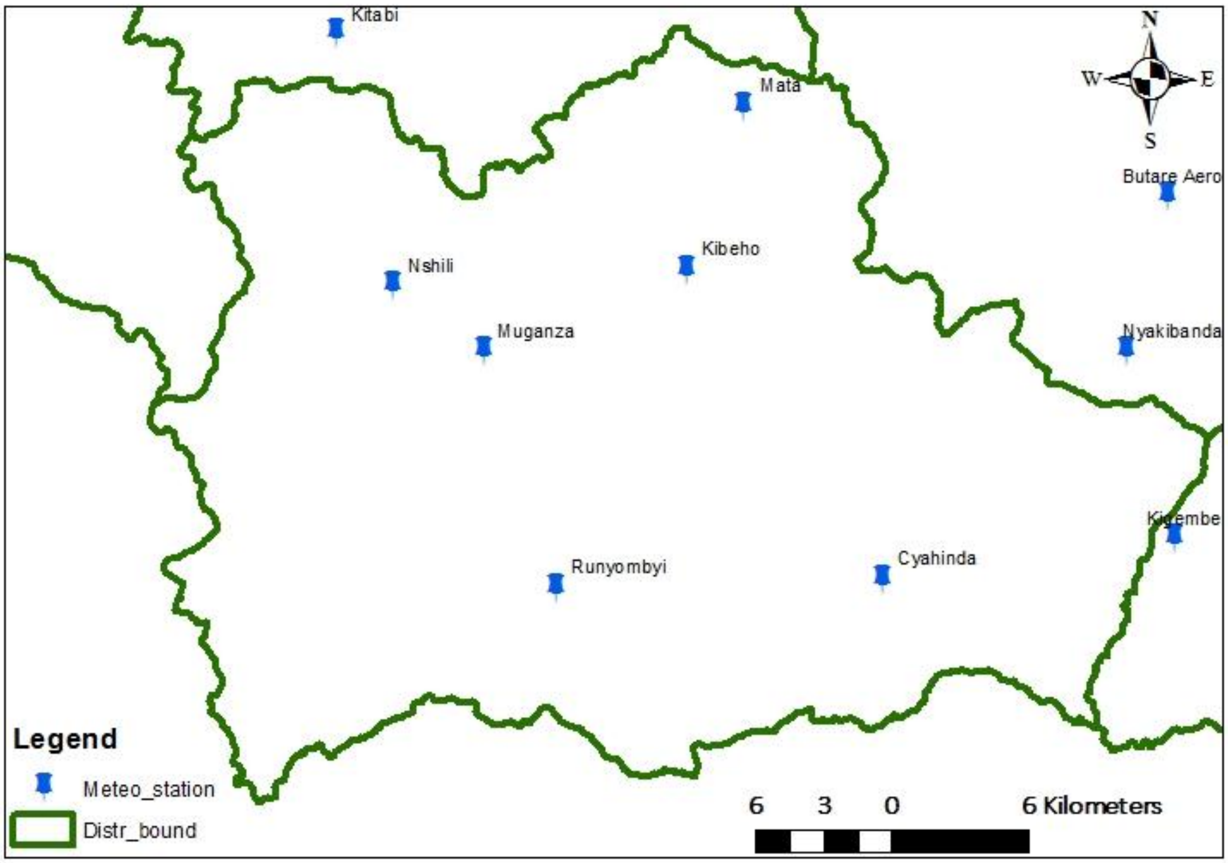


Map1 : Map of the Study Area, Nyaruguru district

The study area was selected based on its climatic conditions and the proximity to a rainy forest, Nyungwe National Park. Moreover, Nyaruguru district was selected as the study area because it is one among main growing coffee district that is attracting many investors. Nyaruguru is mainly a rural mountainous area characterized its ranges between 1600 and 1800m altitude, with some peaks (2000m and more). In fact, in 2015/2016 fiscal year, 1,514.378 T of cherries and 305.142 T of fully washed coffee was produced. Agriculture is the backbone of Nyaruguru economy and the majority of households are currently engaged in some sort of crop or livestock production activity (http://nyaruguru.gov.rw, 2018).

3.2. Nyaruguru Meteorological stations map

Nyaruguru district accounts six meteorological stations distributed randomly across the district as within the map bellow.



3.3. Data acquisition

The data on the existing coffee farms was acquired from "Mainstreaming climate change in the coffee sector in Rwanda" project funded by the Rwanda's Climate change and environment fund and it is being implemented by the Ministry of Agriculture and Animal Resources (MINAGRI), and involves National Agricultural Export Development Board (NAEB), the Rwanda Agriculture Board (RAB) and Sustainable Harvest Rwanda, with technical support from Agri-TAF project. The existing coffee plantations and potential extension sites were mapped in May 2017 by the project team and then converted into shape files.

Temperature and precipitation conditions are considered to be important factors in defining potential coffee yield (Haggar and Schepp, 2012). The current monthly precipitation, monthly temperature data were acquired from Rwanda Meteorology Agency. The Rwanda Meteorology Agency has generated over 30 years (1981 to present) of rainfall and over 50 years (1961-2016) temperature time series using Joyce *et al.* (2004) dekadal methodology for 10-daily time scale and for every 5km grid point across Rwanda. The monthly projection data over 30 years was acquired using the Climate Reanalyzer. Climate Reanalyzer is a platform for visualizing climate and weather datasets. The site is coded and maintained by Dr. Sean Birkel through support from the Climate Change Institute and School of Earth and Climate Sciences of the University of Maine, and partial support from the National Science Foundation (Climate Reanalyzer, http://cci-reanalyzer.org), Climate Change Institute, and University of Maine, USA.

The 30 years projected temperature data were acquired considering the IPCC's The Fifth Assessment Report (AR5) global warming increase (°C) projections (IPCC, 2014). In fact, Representative Concentration Pathways (RCPs) are four greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014. It supersedes Special Report on Emissions Scenarios (SRES) projections published in 2000. Two scenarios will be considered in this study: RCP4.5 is a scenario that stabilizes radiative forcing at 4.5 W m^{-2} in the year 2100 without ever exceeding that value. Simulated with the Global Change Assessment Model (GCAM), RCP4.5 includes long-term, global emissions of greenhouse gases, short-lived species, and land-use-land-cover in a global economic framework (Thomson *et al.*, 2011). On the other side, RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and GHG emissions in absence of climate change policies (Riahi *et al.*, 2011).

The Soil and Terrain database of Central Africa (SOTERCAF, version 1.0) was compiled at scale 1:2 million for the Democratic Republic of Congo and at scale 1:1 million for Rwanda and Burundi. The SOTERCAF compilation has been a joint collaboration of the Soil Science Laboratory of the University of Ghent, Belgium and ISRIC - World Soil Information, Wageningen under contract with the Food and Agriculture Organization of the United Nations. Further assistance is provided by the Department BIOT of the Hogeschool Gent, the Royal

Museum for Central Africa (Tervuren) and data holders in the Democratic Republic Congo, Burundi and Rwanda. The project started in September 2005 by deriving physiographic units from SRTM grid data based on SOTER landform definitions. The database was completed in July 2006 after combining the physiographic layer with the lithology and soils layer. The border harmonization with the SOTERSAF database was finalized November 2006.

Thus, the soil characteristics which include texture, and pH soil was sourced from the SOTER-based soil parameter estimates for Central Africa - DR of Congo, Burundi and Rwanda. The scientific land evaluations analysis allows identifying the main limiting factors for the agricultural production and enables decision makers to develop crop managements able to increase the land productivity (Abdelrahman *et al.*, 2016) . This study focused on coffee only.

The administrative boundaries of the Republic of Rwanda and its devolved provinces, districts, sectors, cells and villages were acquired on August 13^{th}, 2018 from the National Institute of Statistics of Rwanda's website. The data was created in 2006 and updated by the 2012 Census. The census started in 2011 and ended in 2012, where a team of 80 field staff collected census and administrative boundaries up to the lowest administrative level which is "Umudugudu". Boundaries were adjusted in the GIS lab using the 2008-2009 aerial photographs (Orthophoto) taken by the Rwanda Natural Resource Authority. The data format is in decimal degrees using the World Geodetic System (WGS) 1984. Those data will be used mainly in delimiting the study area while modelling.

The Climate System Analysis Group's Climate Information Portal is a web interface that integrates two important information sources into one easy to use interface. It is a climate database that stores and manages queries to a large suite of observational climate data as well as projections of future climate.

Datasets used during this study

Data to collect	**Description**	**Source**
Climate (precipitation, temperature) and	Monthly Precipitation (1981-2017) and temperature (1961-2016) time series reconstructed from station observations	Rwanda Meteorological Agency

weather stations	and remote sensing proxies.	
Projected Climate data (precipitation and temperature)	Climate Reanalyzer utilizes and provides access to existing publicly-available datasets and models.	Monthly climate data from Climate Reanalyzer (http://cci-reanalyzer.org) visited on August 13th 2018, Climate Change Institute, University of Maine, USA.
Topography (Elevation and slop)	The Soil and Terrain database of Central Africa (SOTERCAF, version 1.0) was compiled at 1 km² spatial resolution.	The topographic map of Rwanda was sourced from Van Engelen VWP *et al.*, 2006. Soil and Terrain Database of Central Africa (DR of Congo, Burundi and Rwanda). Report 2006/7, (available through: http://www.isric.org), ISRIC- World Soil Information, Wageningen.
Soil texture and pH	The SOTER-based soil parameter estimates for Central Africa - DR of Congo, Burundi and Rwanda	Batjes N.H. (2007). SOTER-based soil parameter estimates for Central Africa - DR of Congo, Burundi and Rwanda (SOTWIScaf, ver. 1.0). Report 2007/02, ISRIC - World Soil Information, Wageningen.
Administrative boundaries	District boundary data contains District boundaries for Rwanda according to the administrative structure in place between 2001 and 2005. The data was created in 2002 during the 2002 Census. District is	The shape files were sourced from the National Institute of Statistics of Rwanda's website on August 13th, 2018.

	one of an administrative entity in Rwanda's administration and it is under Province authority. It is worth noting that the suitability of coffee may not be respecting these administrative boundaries.	
Coffee productivity	This report provided information of coffee production in Nyaruguru district per sector and per coffee washing station	Nyaruguru 2015/2016 coffee production report.

Table 1: Datasets used in this study

3.4. Data processing and analysis

The process will start with the acquisition and processing of data. In fact, data preparation process includes the preprocessing, classification, standardization and reclassification of various datasets. Preprocessing was performed to improve qualitative judgements concerning the data (Mohd, 2009).

Classification is the process of delineate boundaries of classes in dimensional space and assign class names to pixels using those boundaries while sorting or arranging entities into groups or categories. Thus, climatic, topography and soil factors influence coffee growth were classified into different classes using GIS automated and manual methodology accordingly. Remotely sensed data provide timely, accurate and reliable information on land (Abdelrahman *et al.*, 2016) while the analytical hierarchical process (AHP) considers a set of evaluation criteria, and a set of alternative options among which the best decision is to be made (Saaty, 1980).

After processing, all data sets will be imported in the geodatabase in feature class and raster formats. By using data stored in geodatabase various standardization of the various criteria into a common standard will be performed. The AHP will be used to determine the weights of the criteria based on a common standard using Saaty's scale of numbers 1 to 4 that indicates how many times more important or dominant one element is over another element with respect to the criterion or property with respect to which they are compared (Saaty, 2008). After this step, they were all reclassified and then integrated into one geodatabase. Each of the new reclassified score was then weighted by assigning a percentage influence value. Suitability map outputs were then generated on specific factor studied.

In fact, according to Saaty (2008), the AHP consist of defining the problem and determine the kind of knowledge sought, structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives), constructing a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it, and using the priorities obtained from the comparisons to weigh the priorities in the level immediately below.

3.4.1. Analytical Approaches used during this study

The suitability maps were developed combining GIS Multi-criteria decision-making analysis (MCDA) methodology that integrates GIS, Analytical Hierarchical Process and Remote Sensing technics. In fact, GIS is often recognized as a decision support system involving the integration of spatially referenced data in a problem solving environment while MCDA provides a rich collection of techniques and procedures for structuring decision problems, and designing, evaluating and prioritizing alternative decisions (Malczewski, 2006). MCDA methods are integrative evaluation methods in the sense that they combine information about the performance of the alternatives with respect to the criteria (scoring) with subjective judgements about the relative importance of the evaluation criteria in the particular decision-making context (weighting) (Saarikoski *et al*., 2015). The weight of a measured value depends on its distance from the prediction location; there is a mild decrease in a point’s influence as it gets farther from the prediction. Thus, the value close to the optimum conditions has high value. In this study the index weight was attributed from 1 to 4, and 4 being less influencer factor. The GIS-MCDA provides powerful techniques for the analysis and prediction of hazards (Feizizadeh and Blaschke, 2013).

An inverse distance interpolation is one of the simplest and most popular interpolation techniques. It combines the proximity concept with the gradual change of the trend surface. The advantage of the inverse distance technique is that it can be easily applied in any number of dimensions and provide reasonable estimates (Babak and Deutsch, 2009). The dependency of temperature on elevation needs to be recognized and incorporated into temperature interpolation methods (Li *et al.,* 2000).

Elevationally Detrended Ordinary Kriging uses DEM and the regional regression relationship between temperature and elevation to get the vertical trend at all other locations (Li et al., 2000) while the Inverse Distance Interpolation establishes a regional regression relationship between temperature and elevation from temperature observations and station elevations for each calculation time step. Thus, with only five meteorological stations in the study area, Elevationally Detrended Ordinary Kriging methodology was used for temperature while Inverse Distance Interpolation was used for precipitation.

Finally, weighted overlay is one method of modeling suitability that was used in this study. The following process for Arabica coffee suitability in Nyaruguru were performed; each raster layer is assigned a weight in the suitability analysis based on literature reviewed Table 9. Climatic conditions weights 55%, topographic 25% and soil 20%. Thus, values in the rasters are reclassified to a common suitability scale and raster layers are overlayed, multiplying each raster cell's suitability value by its layer weight and totaling the values to derive a suitability value. These values are written to new cells in an output layer. The symbology in the output layer is based on these values. Assigning a weight to each raster in the overlay process allows us to control the influence of different criteria in the suitability model.

3.4.2. Software Used

ArcGIS 10.6 package was used for integration between remote sensing and geographic information system to arrive at the suitability maps for decision making. The geographic information system was used to create and analyze the suitability maps while Microsoft Excel 2013 was used to illustrate the projected temperature and precipitation data produced by the Climate System Analysis Group's Climate Information Portal of Climate System Analysis Group, University of Cape Town.

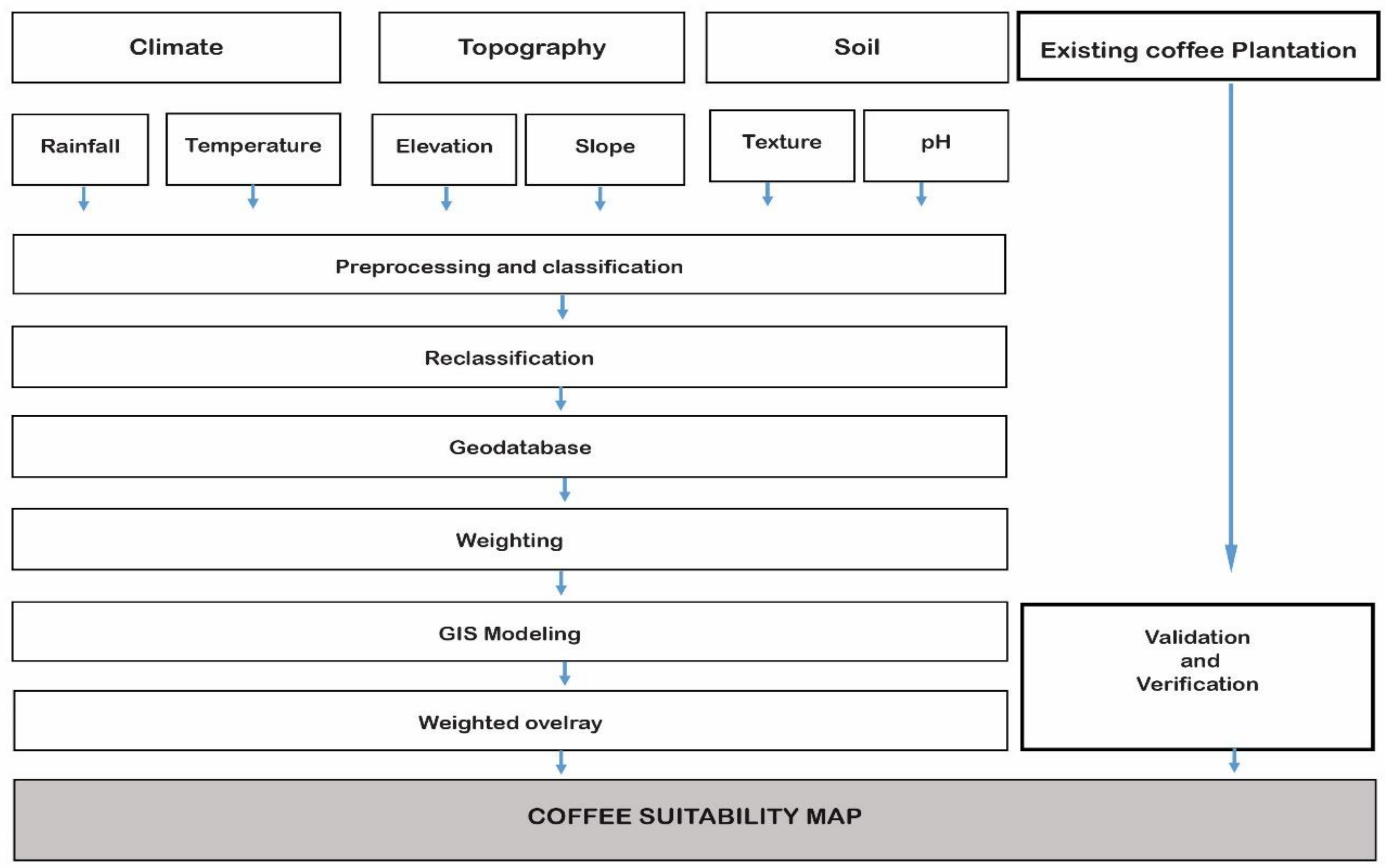
3.4.3. Model Validation

Validation is the task of demonstrating that the model is a reasonable representation of the actual system: that it reproduces system behavior with enough fidelity to satisfy analysis objectives

(Hillston, 2003). Having determined the weights, a GIS-based model is created and combined with the weighted overlay tool and used to link and overlay all the criteria with their respective weights to produce suitability Maps. Validation, verification and comparative analysis for Arabica coffee are thereafter undertaken to confirm the accuracy of the results. In order to validate the data, GPS points are collected in current coffee growing in Nyaruguru district and their productivity were compared to the productivity of other area.

3.4. Research Methodology Flowchart

After collecting data from the dataset listed above and integrating them into ArcGIS; climatic, topographic and soil shape files are produced for the following six factors studies: temperature, precipitation, slope, elevation, pH and soil sandy concentration. For each factor, a suitability map is produced after weighting and classifying them based on information from the literature review. To produce the Arabica coffee suitability map, all the six factors were integrated into one geodatabase after being reclassified and then weighted. The GIS multi-criteria decision-making analysis' weighted overlay to produce suitability map was carried out. To verify the suitability, the existing coffee growing coordinate were collected and then projected to the suitability map to see if they are located in that area in order to assess coffee productivity in the study area and compare it to other area using random methodology.


Climate
Topography
Soil
Existing coffee Plantation
Rainfall
Temperature
Elevation
Slope
Texture
pH
Preprocessing and classification
Reclassification
Geodatabase
Weighting
GIS Modeling
Weighted ovelray
Validation
and
Verification
COFFEE SUITABILITY MAP

CHAPTER 4. RESULTS

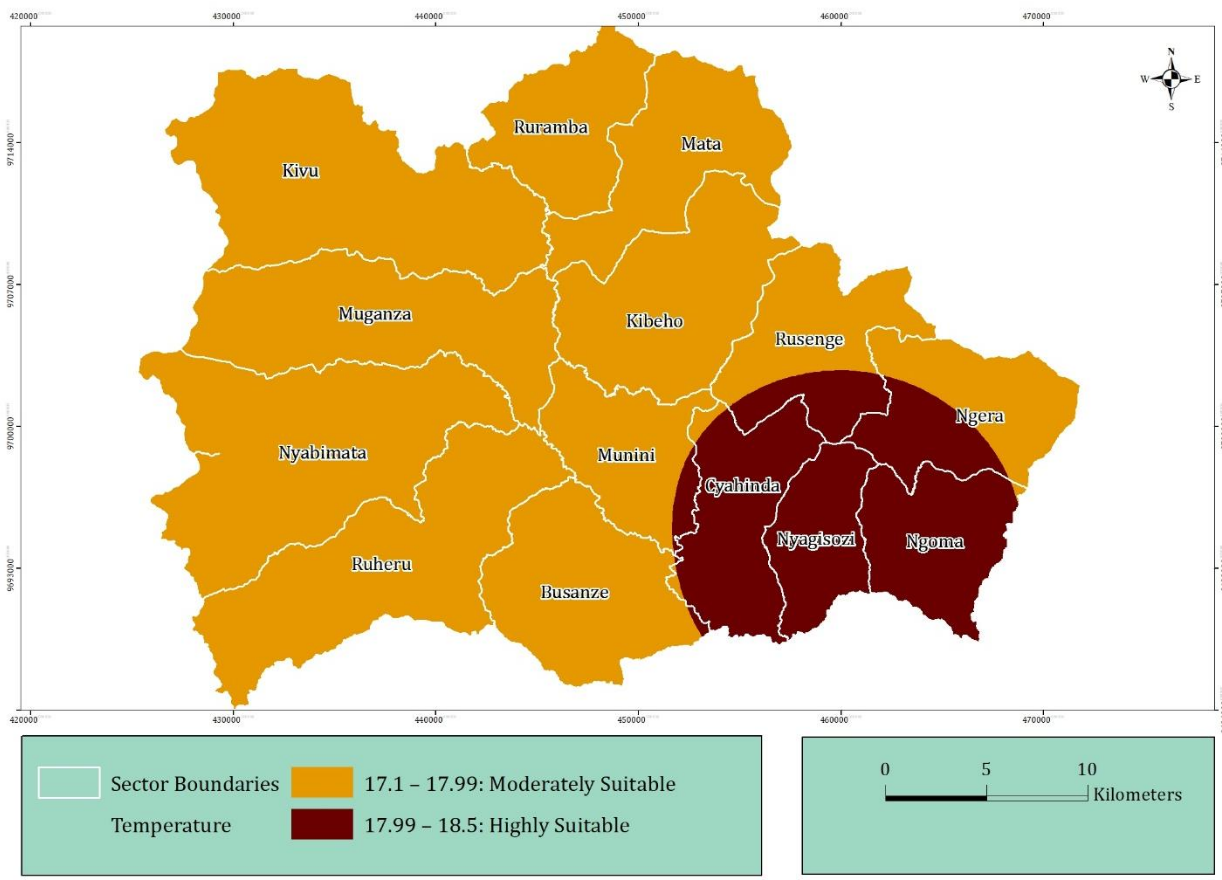
This section presents the findings of the study on suitability Analysis of Coffee Growing Area in Rwanda in the context of climate change, case of Nyaruguru district.

4.1. Nyaruguru climatic conditions

The monthly current and projected temperature and precipitation for the coming 30 years were analyzed and the results are presented in the section below.

4.1.1. Temperature suitability for Arabica coffee

The annual mean temperature map shows that the suitability increases from the western part that touches on Nyungwe National Park to the southeastern part of Nyaruguru from moderate to highly suitable respectively (Map 2).



Map2 : Temperature suitability for Arabica coffee

The temperature map obtained was classified into two classes and then suitability index attributed to each class (Table 1). The map bellow shows the temperature suitability for the period 2016 in Nyaruguru district.

Temperature Range in ^{o}C	Class	Index weight
17.1 – 17.99	Moderate to suitability	2
17.99-18.5	Highly suitable	1

Table 2: Temperature Classes and suitability Index weight

4.1.2. Historical, current and projected Temperature

The temperature as one of the most critical environmental factors that exerts a great influence on coffee plant physiology was assessed for Nyaruguru district. On the intervals of 30 years before and after 2016, considered as starting point due to availability of data, temperature historical records and projections revealed an increase of temperature over time (Figure 3).

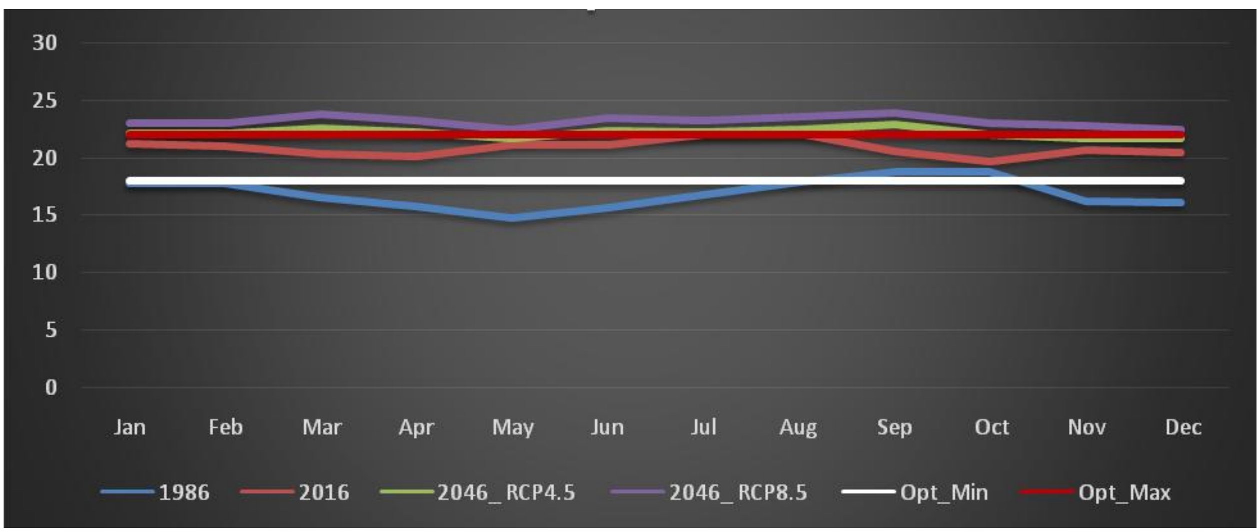


Figure3: Nyaruguru's historical, 2016 and projected temperature under RCP4.5 and RCP8.5 Scenarios.

The data reveals that Nyaruguru temperature was fluctuating between 16°C and 18°C in 30 years before 2016 while projections show temperature increase of 1.30^{o}C in RCP4.5 scenarios and about 2.25°C in RCP8.5 Scenario in coming 30 years and beyond.

Table 3: The Fifth Assessment Report (AR5) global warming increase (°C) projections

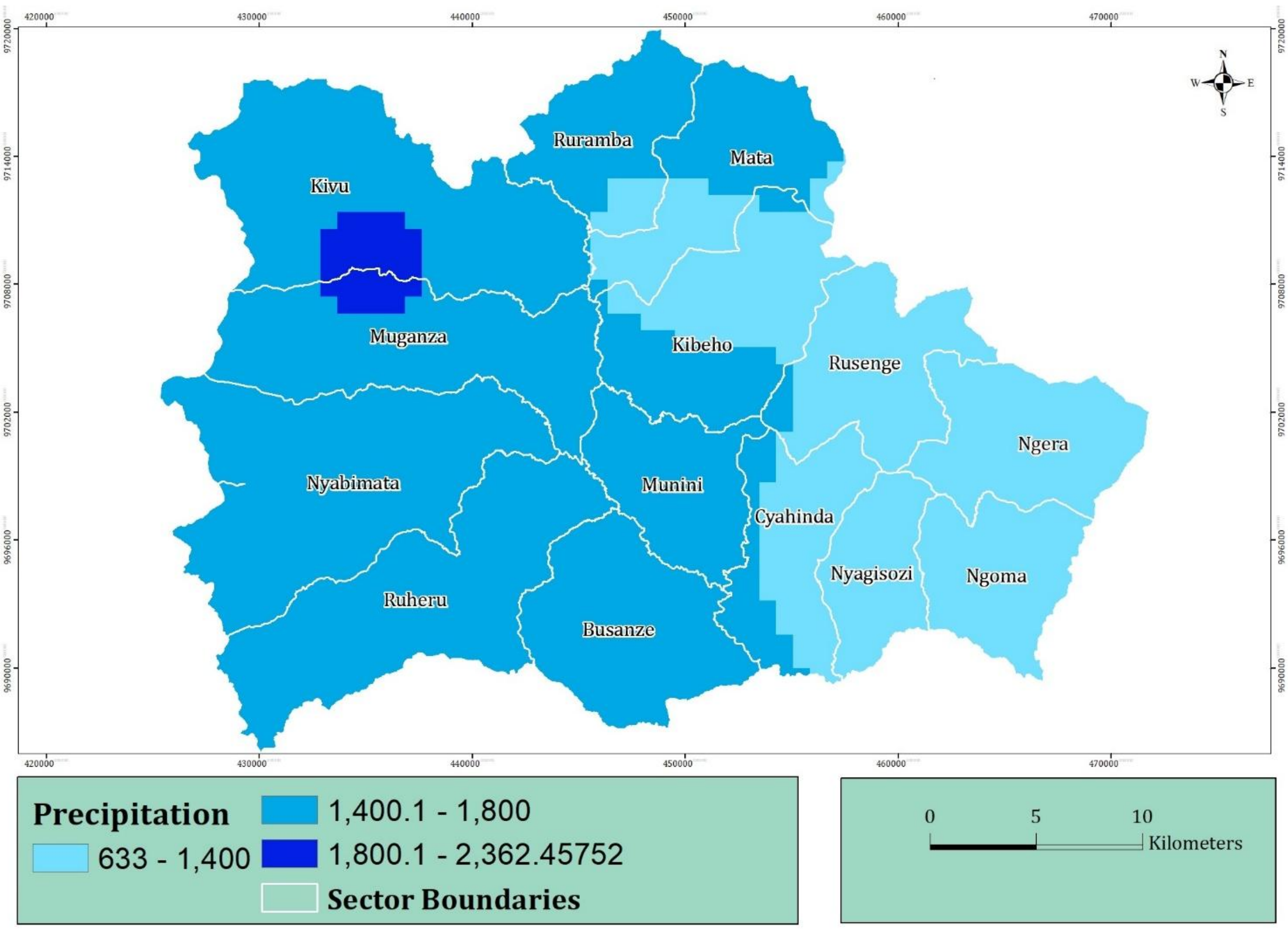
	2046-2065
Scenario	Mean and likely range
RCP2.6	1.0 (0.4 to 1.6) °C
RCP4.5	1.4 (0.9 to 2.0) °C
RCP6.0	1.3 (0.8 to 1.8) °C
RCP8.5	2.0 (1.4 to 2.6) °C

4.1.3. Precipitation suitability analysis for Arabica Coffee

The precipitation map shows that the large part of Nyaruguru is currently highly suitable for growing Arabica coffee with its annual precipitation ranging from 1,246 to 1,642 mm (Map4). The precipitation map obtained was classified into 4 classes and suitability index attributed to each class (Table3). The map bellow shows the precipitation suitability for the period of 2016 in Nyaruguru district.

Table 4: Precipitation Classes and suitability Index weight

Precipitation Range in mm	**Class**	**Index weight**
633 – 1,000	Marginal to Moderate	4
1,001 – 1,400	Suitable	2
1,401 – 1,800	Highly Suitable	1
1,801 – 2,363	Unsuitable	3



Map4: Precipitation suitability analysis for Arabica Coffee

4.1.4. Historical, current and projected precipitation

The precipitation is also in important climatic condition in assessing coffee suitability. The historical, current and projected precipitation were studied (Figure 5). This study reveals that the projected precipitation will decrease slightly in the first quarter of the year and then decrease slightly in the last quarter of the year compared to the historical records of 1986 and the projections shows that precipitation will fluctuate within the same range as the current situation.

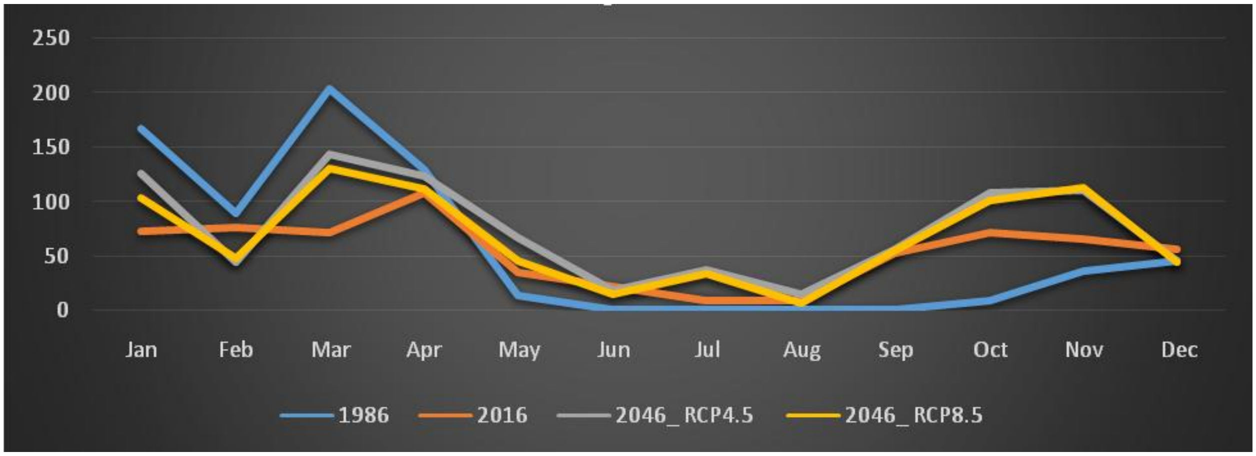


Figure 5: Nyaruguru's historical, current and projected precipitation

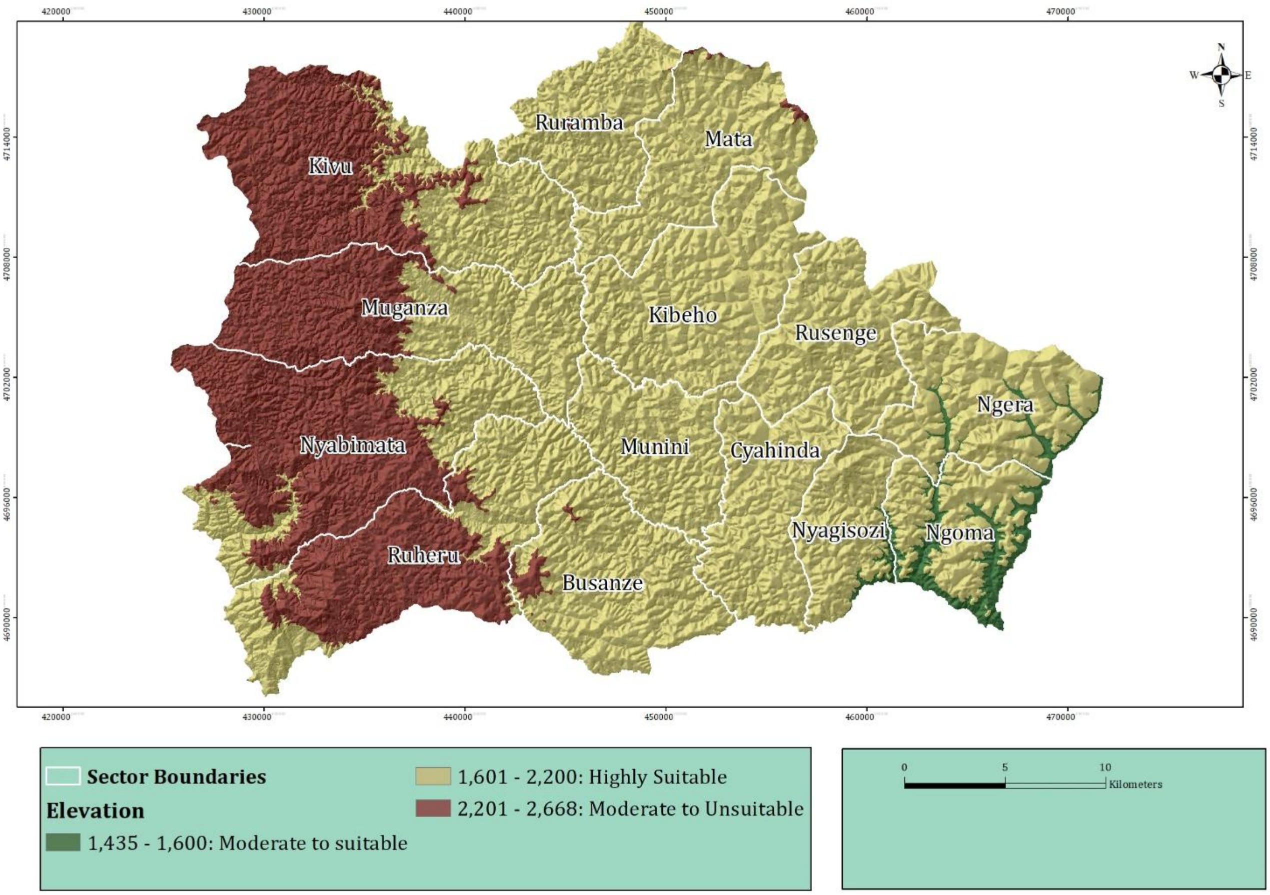
4.2. Topography conditions

4.2.1. Elevation suitability for Arabica Coffee

The elevation map extracted from the Digital Elevation Model (DEM) shows the area that have the elevation ranging from 1,600 - 2,200 m which is highly suitable for Arabica coffee while sectors of Nyaruguru that have elevation above 2,200 m that located within or bordering the Nyungwe National Park have higher elevation which is fluctuating from moderate to unsuitable for Arabica coffee as in Map 6. The elevation map obtained was classified into 3 classes and suitability index attributed to each elevation class (Table 5).

Table 1: Elevation Classes and suitability Index weight

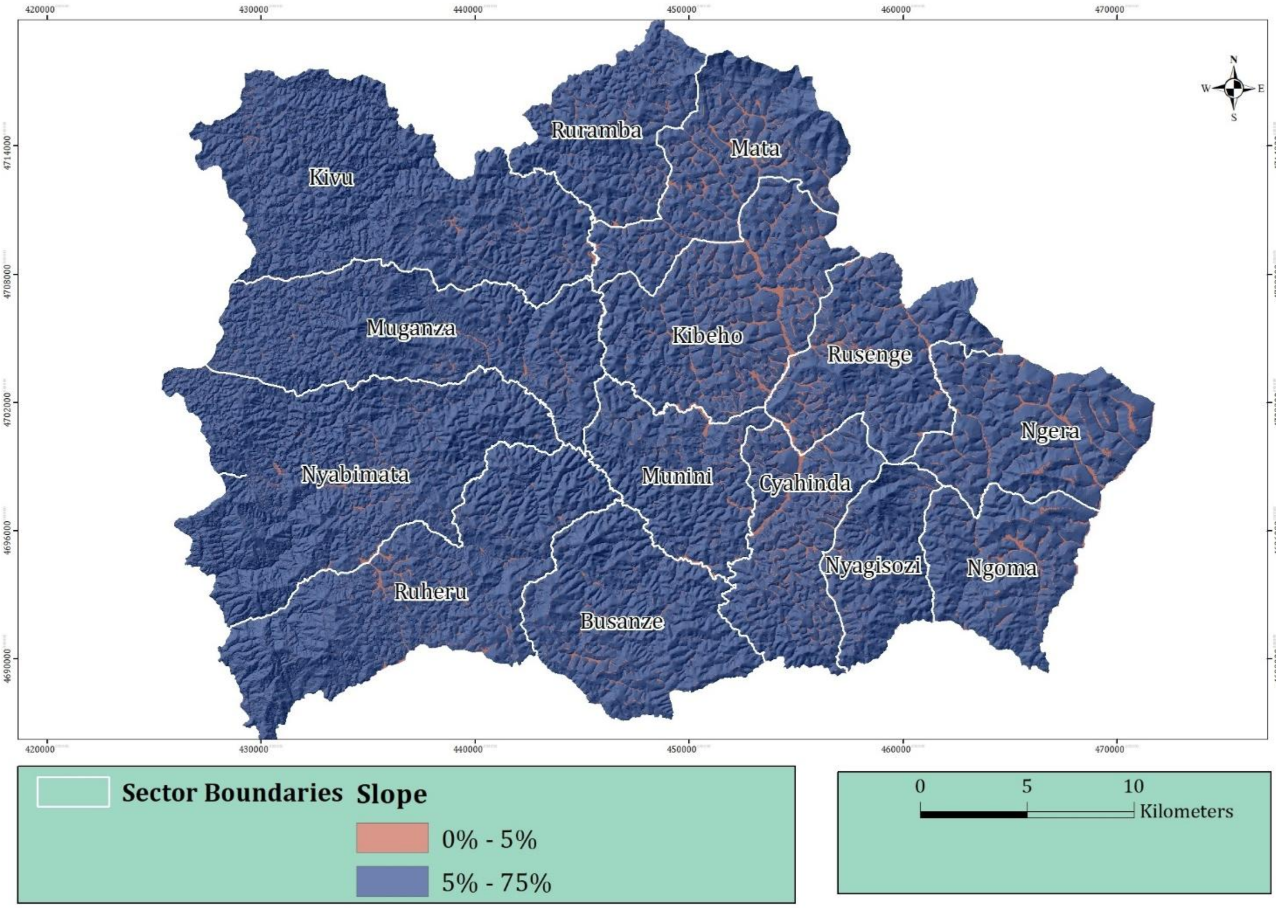
Elevation Range	Class	Index weight
1,435 - 1,600	Moderate to Suitable	2
1,601 - 2,200	Highly Suitable	1
2,201 - 2,668	Suitable to Moderate	3



Map 6: Elevation suitability for Arabica Coffee

4.2.2. Slope suitability for Arabica Coffee

The slope was extracted from the Digital Elevation Model (DEM) and then reclassified into 2 classes and weight index was assigned (Map 7). The classification was based on Kuit *et al.*, (2004). A large part of Nyaruguru district has a slope greater than 5% which is relevant for quality but critical during extreme events such as prolonged precipitation or heavy precipitation that could lead to landslide as the slope increase. Thus, contour farming or other conservation practices to avoid soil quality loss should be considered (Table 6).



Map7: Slope suitability for Arabica Coffee based on topography of the area

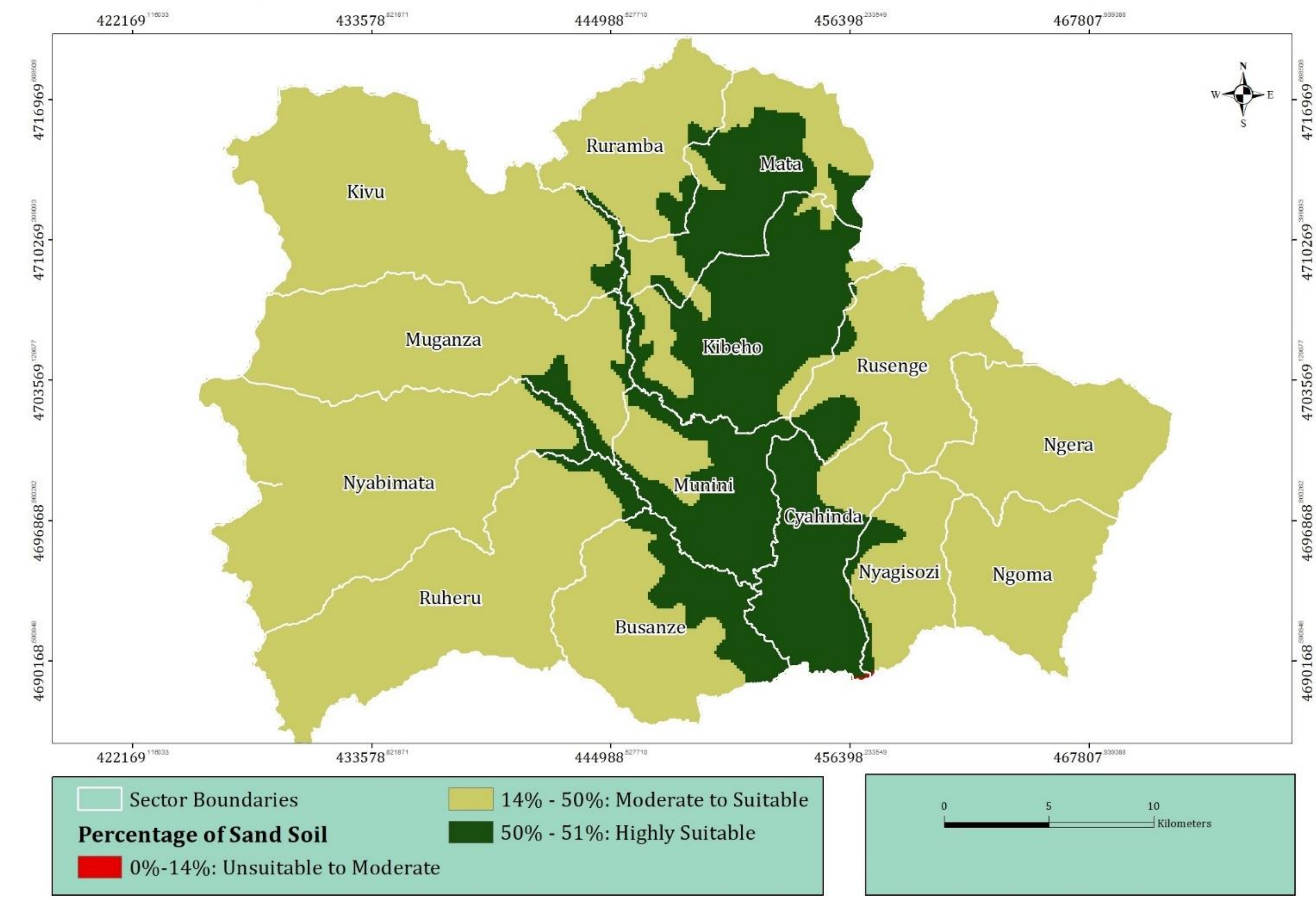
Table 2: Slope Classes and suitability Index weight

Slope percentage	Farming practices	Index weight
0% - 5%	No Contours needed	1
5% - 75%	Contours needed	2
75% - 100%	No Data	NA

4.3. Soil conditions

4.3.1. Soil Texture suitability for Arabica Coffee

In this section, only sandy soil content was considered. Sandy soils are those that are generally coarse textured until 50 cm depth and consequently retain few nutrients and have a low water holding capacity. The sandy soil content map obtained (Map 8) was reclassified into three classes based on their concentration of sandy soils (Table 7). The map shows that the central part of Nyaruguru is highly suitable and the remain is moderate to suitable.



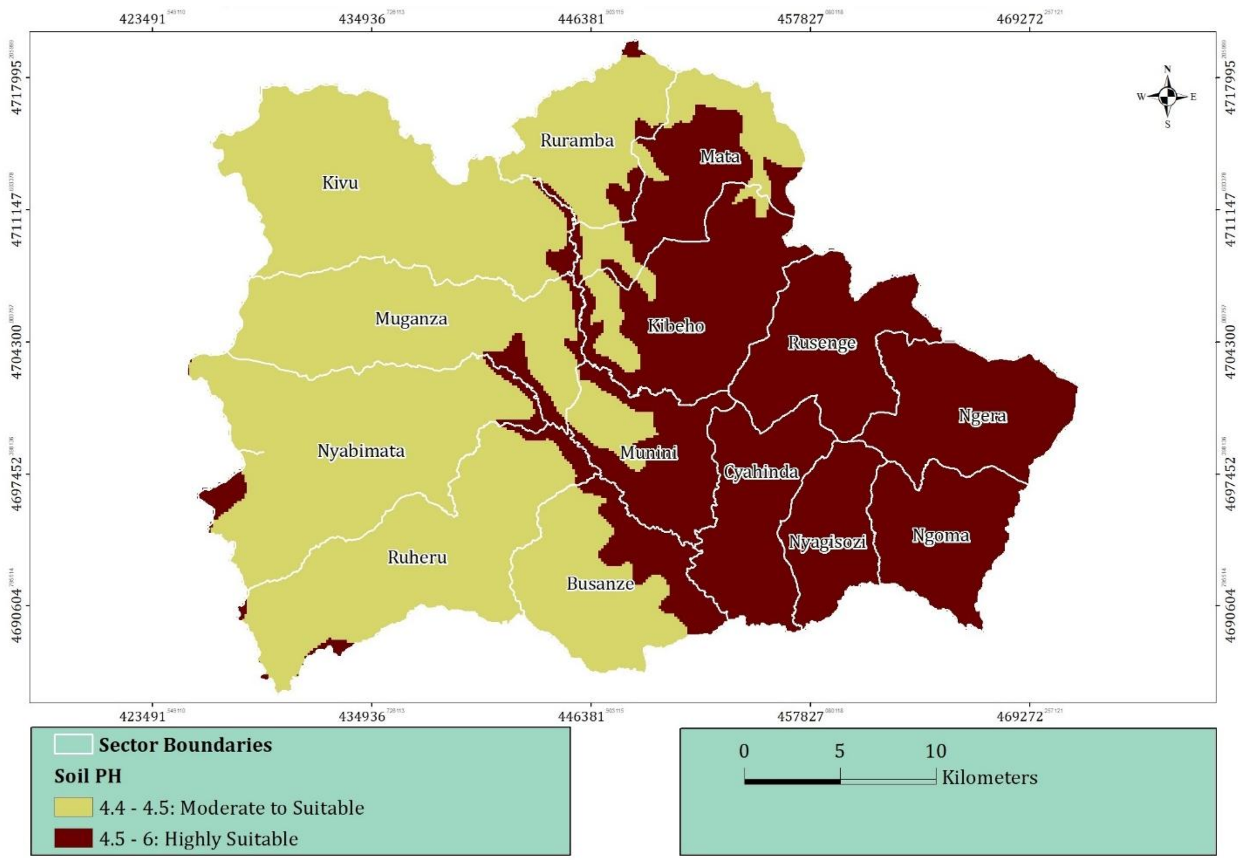
Map8: Soil Texture suitability for Arabica Coffee

Table 3:Slope Classes and suitability Index weight

Sandy percentage	Class	Index weight
0%-14%	Unsuitable to Moderate	3
14% - 50%	Moderate to Suitable	2
50% - 51%	Highly Suitable	1

4.3.2. pH suitability for Arabica Coffee

The pH soil content Map obtained (Map 9) was reclassified into two classes based on their acidity and alkalinity (Table 8). The map reveals that in the central to eastern part of Nyaruguru the soil is highly suitable for Arabica coffee growing considering soil pH while the remain part is moderate to suitable.



Map9: pH suitability for Arabica Coffee

Table 4:pH Classes and suitability Index weight assigned

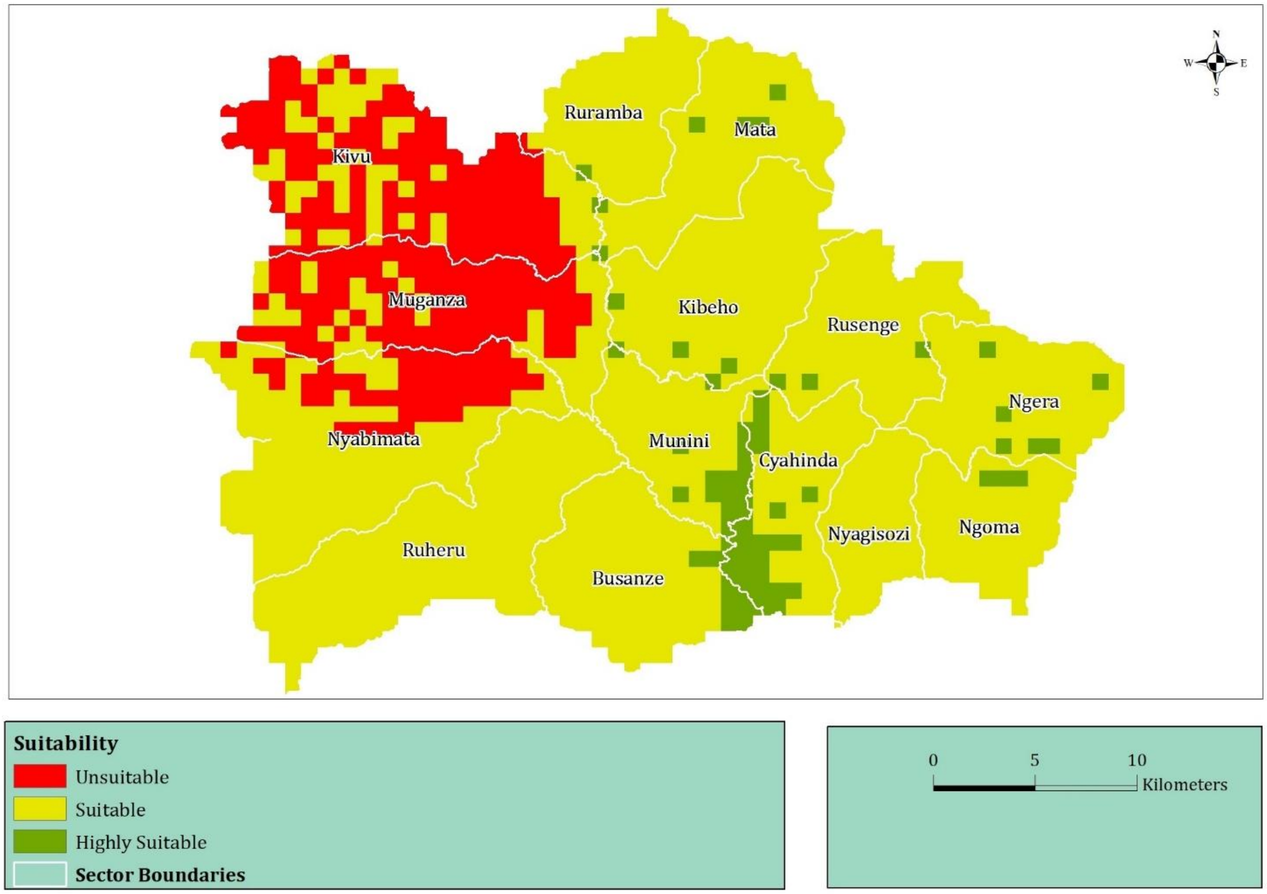
Soil pH	Class	Index weight
4.4 - 4.5	Moderate to Suitable	2
4.5 - 6	Highly Suitable	1

4.4. Arabica Coffee suitability in Nyaruguru district

Overlay techniques were used to generate the Arabica Coffee Suitability Map for Nyaruguru district (Map 10). The suitability map was generated combining climatic, topographic, and soil conditions. Based on the literature review and ideal Arabica coffee growing conditions, the weight was assigned (Table 9) to generate the suitability map. The suitability map shows that 77.6% of Nyaruguru is suitable and 4% is highly suitable while about 17.9% of Nyaruguru district is unsuitable and the limiting factors is high precipitation.

Table 5: Overlay % table.

	Factors	**%**
Climatic Condition	Temperature	35%
Climatic condition	Precipitation	20%
Topography	Slope	15%
Topography	Elevation	10%
Soil composition	Texture	15%
Soil composition	pH	15%

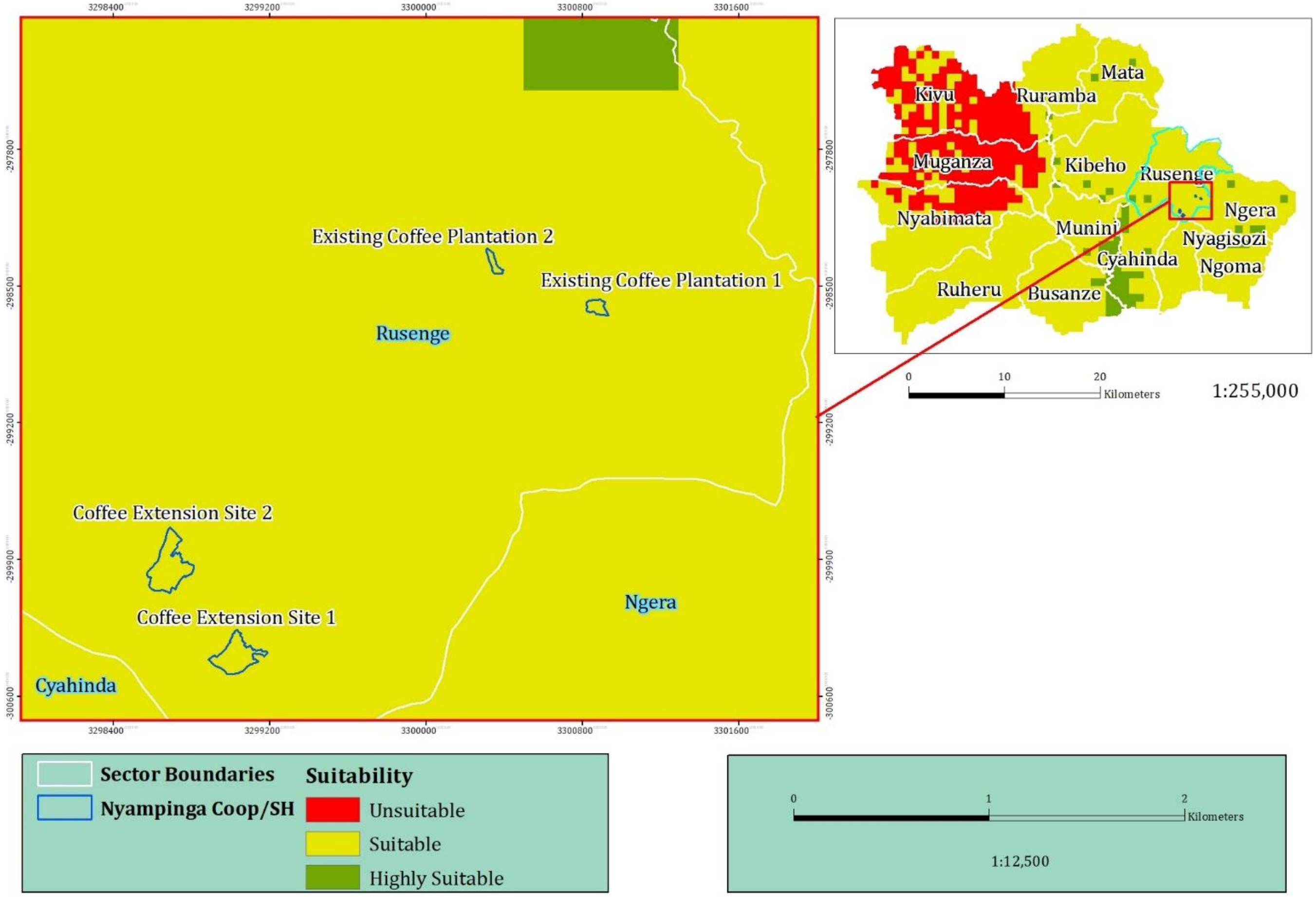


Map10: Nyaruguru District Arabica Coffee suitability map

The suitability analysis for Arabica Coffee in the context of climate change in Nyaruguru district shows that the Norther western part of Nyaruguru district is unsuitable for growing coffee but the remaining big part of the district is suitable for growing coffee with small patches scattered in century and Eastern part of the district highly suitable. Thus, apart the Northern-Western part of Nyaruguru district the remaining part is suitable to Arabica Coffee growing.

4.5. Field Arabica Coffee Suitability Validation data

In order to validate the finding, four plots where two existing coffee plantations and extension sites suggested by local famers based on their indigenous knowledge were mapped and then projected on the suitability map generated as part of this study. The validation map generated using 2016 data shows that the two existing coffee plots mapped are within suitable area and the two extension plots suggested by local famers fall also in the suitability area (Map 11). Thus, this revealed how important is indigenous knowledge in suitability analysis. However, based on projected data, mainly temperature and precipitation, the suitability will change compared to the current situation.



Map11: Field Arabica Coffee Suitability map

According to the data from Nyaruguru district, Nyampinga coffee washing station located in Rusenge sector (Map11) registered 123.883 Tons of cherries and 24.776 Tons of full washed coffee equivalent to 8% of district coffee production in Fiscal year 2015/2016.

CHAPTER 5. DISCUSSION

5.1. Climatic conditions

Considering both RCP4.5 and RCP8.5 scenarios, the projected temperature data for over 30 years from 2016 in Nyaruguru will increase and it is alarming for coffee growing. The temperature that was fluctuating between 16°C and 18°C in 1986 and 2016 respectively will show an increase of 1.30°C under RCP4.5 and about 2.25°C under RCP8.5 Scenarios in coming 30 years and beyond. In fact, Verdoodt and Ranst (2003) concluded their study saying that the temperature will be fluctuating beyond coffee ideal growing conditions in Rwanda that are the temperatures of 18°C–22°C in coming years due to climate change. This is similar to Sachs *et al.*, (2015) conclusion on increase of temperature; the temperature across the coffee belt is expected to rise by 2.1°C making the region less suitable for coffee or causing shifts in other place. Thus, we should expect shifting in suitable coffee growing area in Nyaruguru district. However, the temperature will not reach the threshold of 25°C that affect the plant's photosynthesis process and spur the development of diseases such as coffee leaf rust and fruit blight under any scenarios, and will not go below 15°C to cause spur coffee berry disease (Ngabitsinze *et al.*,2011).

This study reveals also that the projected precipitation will decrease slightly in the first quarter of the year and then decrease slightly in the last quarter of the year compared to the historical records of 1986 and the projections shows that precipitation will fluctuate within the same range as the current situation in coming 30 years. On the other side, the precipitation map shows that the large part of Nyaruguru is highly suitable for growing Arabica coffee with its annual precipitation ranging from 1,246 to 1,642 mm. This is similar to Michon (2015) conclusion saying that the ideal precipitation for Arabica coffee range from 1200 to 1500 mm per year followed by a dry season lasting 2-3 months. Thus the dry season suits best Arabica coffee (Casasbuenas, 2017) by improving quality and yield.

In fact, the temperature and precipitation conditions are considered to be important factors in defining potential coffee yield (Haggar and Schepp, 2012) and its distribution (Ann and Ranst, 2006). Thus, with temperature and precipitation suitability increasing from the central to the eastern part of Nyaruguru, the coffee distribution in the area depending on them as it represents 55% of the whole weight attributed (Bongase, 2017; Li et al., 2000 and Philip, *et al.*, 2009). The spatial variation of coffee productivity in the agro-ecological zones is considerable and is influenced by climatic conditions (Nzeyimana *et al.*,2014), thus they weighted higher compared to other conditions .

Although Arabica coffee species mainly cultivated in Rwanda is sensitive to climate variables, particularly temperature and precipitation (Davis *et al*., 2012), changes in annual precipitation and its seasonality would have little effect (Ovalle-Rivera *et al.*, 2015) as exact amount of precipitation needed by the plant depended on other factors such as soil quality, elevation, slope and ground cover that is assessed in the following part of this study.

5.2. Topographic Condition

In this study, the elevation for Nyaruguru ranging from 1,600 - 2,200 m is highly suitable and cover the larger part of the study area. However, this elevation range is slightly different from Casasbuenas (2017) range of 1,300 and 1,500 m altitude even if he continued saying in the same study that Arabica coffee plantations can still grow well as low as sea level and as high as 2,800 m.. On the other side, the slope map shows that a large part of Nyaruguru has a slope above 5%. This means that contour farming or conservation practices have to be undertaken to avoid erosion and good soil quality loss.

In fact, the topography affects the climate (e.g. variations in temperature and humidity), distribution of soil moisture, soil organic-matter content, soil nutrients, soil textural composition, and soil physical properties, which affect crop growth and yield in a field (Nzeyimana, 2018). Thus, the elevation influences a number of these factors and must be considered along with temperature, precipitation and water supply, soil, slope and aspect when determining where to plant coffee (Pohlan, 2009). Zones that currently have climates better suited for Arabica will migrate upwards by about 500m in elevation. In these zones the up-slope migration will be gradual, but will likely have negative ecosystem impacts (Bunn *et al.*,2015).

5.3. Soil conditions

In this study, with 50% - 51% of sandy composition being highly suitable, the central part of Nyaruguru district is ideal for growing Arabica species while the pH study reveals that from central to eastern part of Nyaruguru with pH ranging from 4.5 to 6 is also highly suitable. Therefore, sandy soil map and soil pH map shows that the central part of Nyaruguru meet the minimum requirement for suitability. Even if the sandy concentration is close to 50% and don’t go beyond, the soil management practices which lead to an increase in the fine fraction are helpful in improving soil properties and crop productivity in this area (Dawson *et al.,*2016). Thus, fertilization of these soils is considered essential. Organic fertilization (with manure, composted coffee pulp, etc.) and lime should be promoted at large scale as these are at the heart of sustainable soil management practices. Such applications maintain and build soil carbon level, and may supply nutrients in a well-balanced ratio(Nzeyimana, 2018).The Food and Agriculture Organization (FAO) of the United Nations recommends: "If a coffee tree is to grow well, it needs more than anything else a soil of good structure, permeable and deep."

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

This study reveals that Nyaruguru district is suitable for growing Arabica coffee species. The Arabica Coffee suitability depends mainly on climatic conditions. Temperature and precipitation conditions are considered to be important factors in defining potential coffee yield. Both factors interfere with the crop phonology, and consequently in productivity and quality(Bongase, 2017). The climatic conditions also play an important role on coffee distribution (Verdoodt and Ranst, 2006). And, Nyaruguru has ideal growing conditions apart a small part covered by Nyungwe Nation Park limited by high precipitation and low temperature. However, the projected data for over 30 years considering both RCP4.5 and RCP8.5 scenarios predict a considerable increase in temperature increase of 1.30°C in RCP4.5 scenarios and about 2.25^{o}C in RCP8.5 scenarios in coming 30 years and beyond if nothing is done. In 2046, Nyaruguru annual temperature will be fluctuating between 22°C and 23°C. Coupled with extreme events such as flooding and heavy rain, climate change impacts on coffee sector in Nyaruguru shall have significant impact on quality and yield if climate smart agricultural and conservation best practices are not adapted overcoming years.

Thus, based on the findings from this study, the following recommendations for the Government, Development Partners and famers respectively were generated;

- ❖ The Government should continue to promote climate smart agriculture to improve coffee production both yield and high quality, and to adapt to climate change focusing on small holder farmers that dominated the agriculture sector mainly coffee sector.

- ❖ Development partners should start to invest in coffee extension focusing in the highly suitable region to avoid the loss of yield and good coffee quality in coming years.

- ❖ Farmers in Nyaruguru should adapt contour farming practices to avoid runoff that could be caused by extreme events such as heavy precipitation or land sliding linked to the changing climate as the area has a moderate to high elevation and slope. In fact, soil erosion, surface run-off and leaching can all pose threats to a successful and high-quality coffee crop by harming soil fertility, causing organic matter to decline and affecting water sources.

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APPENDICES

Appendix 1: Nyaruguru Temperature Raw Data

NCEP Climate Forecasting System Reanalysis (CFSR)
Temperature at 2 meters (degree C)
Values averaged across Region (2.5S-2.5S;29.3E-29.6E)

This file was generated by Climate Reanalyzer (http://cci-reanalyzer.org)
Climate Change Institute; University of Maine; USA (http://climatechange.umaine.edu)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1979	15.96	16.92	16.72	16.06	14.79	15.7	16.57	18.74	19.47	19.3	18.08	16.1
1980	17.87	17.45	17.22	16.84	16.13	17.53	17.47	18.21	20.58	18.83	17.04	17.21
1981	17.71	18.2	18.1	15.83	14.84	15.07	16.43	18.62	19	18.17	17.6	16.94
1982	17.11	17.33	17.19	15.92	15.11	15.34	15.84	18.39	19.08	18.07	15.93	16.36
1983	17.85	18.82	18.36	17.19	16.91	17.16	18.34	19.26	19.97	18.17	17.09	16.59
1984	17.2	17.53	17.17	15.71	16.18	16.55	18.03	19.29	19.81	18.24	16.57	17.49
1985	18.4	17.69	16.92	14.89	14.58	15.7	15.76	17.99	19.27	18.92	16.84	17.4
1986	17.74	17.74	16.45	15.76	14.72	15.62	16.77	17.8	18.74	18.73	16.14	16.06
1987	16.66	17.42	17.44	15.78	14.92	16.1	17.51	18.3	19.98	19.64	17.53	18
1988	17.37	18.41	17.77	16.58	16.08	16.33	17.79	19.5	20.24	19.1	17.44	16.9
1989	17.99	18.23	17.25	15.9	14.94	15.34	16.81	18.41	19.61	19.02	18.33	16.4
1990	17.64	17.45	16.62	16.32	15.1	16.08	16.74	18.9	19.91	19.24	17.32	17.17
1991	17.91	18.96	18.47	16.41	15.91	17.66	17.65	19.61	20.2	18.4	17.61	17.98
1992	19.13	19.63	20.3	17.99	17.4	17.29	17.64	18.25	19.24	19.26	17.69	16.78
1993	17.77	17.52	16.81	16.93	17.02	17.9	17.52	18.85	19.44	19.97	18.07	18.15

1994	18.28	18.63	17.42	17.28	17.06	17.92	17.86	18.88	20.41	18.99	17.55	17.2
1995	18.81	18.29	17.83	16.76	15.95	18.12	18.19	19.16	20.3	19.15	18.87	18.04
1996	17.92	17.55	17.95	15.91	15.9	16.52	17.83	18.48	19.99	19.27	17.27	18.11
1997	17.88	19.13	18.67	15.32	15.03	15.25	16.85	19.24	20.37	19.17	17.12	16.49
1998	17.06	18.7	18.28	17.4	17.76	17.85	18.34	19.72	20.16	20.5	19.22	18.69
1999	18.53	19.76	17.79	16.21	16.13	17.06	17.75	19.01	20.08	19.8	17.73	17.18
2000	18.81	19.09	18.04	17.34	18.23	18.32	18.57	19.91	20.28	19.34	17.87	16.9
2001	17.56	18.36	17.69	16.55	16.95	17.65	18.66	19.87	19.78	19.01	17.33	18.03
2002	17.45	18.24	17.43	16.29	17.29	18.26	19.01	19.82	20.47	19.74	17.82	17.52
2003	18.36	19	18.46	17.41	16.44	17.39	18.07	19.76	20.26	19.53	18.4	18.22
2004	18.16	18.02	18.09	16.46	16.44	16.66	17.45	19.81	19.34	18.91	17.97	17.5
2005	17.7	18.95	17.91	17.87	16.87	17.09	17.73	19.65	20.56	19.63	18.65	18.86
2006	18.9	18.89	17.48	15.83	15.51	15.67	17.31	18.68	19.55	19.63	17.09	16.8
2007	17.47	17.57	16.89	16.32	15.67	16.14	16.82	18.29	19.33	18.53	17.53	17.23
2008	17.69	17.06	16.58	15.48	15.68	14.91	16.57	18.06	20.03	18.56	17.71	17.77
2009	17.55	17.41	17.2	16.44	15.96	16.43	17.28	19.35	20.51	19.09	17.42	17.64
2010	17.57	18.17	17.65	17.15	16.66	16.67	17.68	19.61	19.31	18.93	17.81	17.02
2011	14.69	14.9	14.61	14	13.84	13.83	14.13	15.03	14.88	14.22	14.64	14.82
2012	15.33	14.49	15.02	14.16	13.73	13.1	14.41	15.36	15.56	14.99	14.32	14.62
2013	15.13	15.02	14.87	14.46	13.66	13.64	14.33	14.56	15.42	14.53	14.72	14.54
2014	15.2	15.12	14.83	14.58	13.86	13.61	14.23	14.6	14.67	14.78	14.07	14.86
2015	15.22	15.22	14.58	14.63	14.04	14.09	14.39	16.03	16.19	15.1	14.69	15.13
2016	15.52	15.81	16.04	15	14.65	13.18	14.52	15.67	15.91	15.27	14.18	14.35

Appendix 2: Nyaruguru Precipitation Raw Data

NCEP Climate Forecasting System Reanalysis (CFSR)
Total Precipitation (mm)
Values averaged across Region (2.5S-2.5S;29.3E-29.6E)

This file was generated by Climate Reanalyzer (http://cci-reanalyzer.org)
Climate Change Institute; University of Maine; USA (http://climatechange.umaine.edu)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1979	162.73	248.94	63.83	119.74	26.07	11.43	4	0.17	0.31	21.1	53.73	137.34
1980	182.04	79.91	202.14	175.92	63.89	2.13	1.2	1.12	2.14	16.89	79.56	131.04
1981	102.89	91	130.47	333.91	49.49	16.07	1.36	0.23	27.48	18.84	33.72	98.78
1982	112.05	124.88	75.17	130.66	30.4	2.39	1.06	0.57	10.18	37.9	147.1	210.79
1983	82.77	123.53	151.55	70.99	18.38	6.63	3.61	0.92	3.9	41.27	101.56	180.19
1984	150.03	136.1	91.3	58.21	11.36	3.41	1.89	36.08	1.32	26.68	123.76	87.66
1985	48.49	234.64	97.41	66.45	22.26	0.86	0.05	0.26	1.47	7.66	111.49	47.91
1986	136.66	95.07	88.05	81.54	84	14.48	1.24	0	4.11	38.93	89.25	274.1
1987	327.79	193.69	179.87	85.84	39.03	9.61	1.25	4.15	4.02	11.99	113.25	20.06
1988	166.6	89.57	203.67	129.75	13.96	2.31	0.54	0.67	1.23	8.72	36.45	46.14
1989	101.64	131.79	135.97	178.36	31.78	16.66	1.03	1.64	1.08	10.49	43.5	223.34
1990	154.81	245.8	224.51	216.77	12.6	3.01	0.23	2.17	2.56	21.47	98.66	79.35
1991	79.66	66.52	189.66	85.04	50.72	8.78	2.25	0.15	2.2	33.87	19.59	70.8
1992	35.35	24.45	14.5	164.15	69.02	1.87	0.42	0.12	0.11	2.84	66.45	138.9

1993	151.99	155.79	153.5	42.99	43.05	0.54	0.4	4.61	0.51	8.93	33.52	45.06
1994	137.85	84.01	242.55	121.18	58.23	0.33	0.93	0.44	0.7	11.48	71.4	60.9
1995	50.11	177.16	116.18	81.31	38.19	3.19	0.29	0.13	0.78	16.89	14.14	114.05
1996	142.25	173.28	134.46	93.02	28.85	20.52	3.63	0.09	16.64	30.52	60.71	33.94
1997	104.13	32.76	65.85	125.36	104.38	4.53	4.27	0.1	0.05	17.86	299.64	315.57
1998	251.87	122.9	173.77	130.42	156.08	24.86	6.75	1.74	3.67	15.06	20.91	63.13
1999	188.27	30.34	323.72	110.73	19.14	2.06	2.05	1.9	1.19	3.3	45.48	83.03
2000	60.13	75.71	133.4	183.59	5.19	4.22	0.44	1.74	1.72	72.1	198.13	274.06
2001	329.04	138.4	173.89	143.77	86.72	3.16	0.84	2.46	42.31	61.54	86.35	115.47
2002	304.87	197.62	171.62	94.29	114.93	1.63	2.22	0.48	12.86	14.82	133.32	223.43
2003	209.85	118.03	129.21	158.25	150.55	7.78	1.07	3.49	4.77	35.33	45.71	74.1
2004	171.2	207	213.89	185.87	74.64	2.76	0.56	0.98	77.68	19.6	63.58	242.73
2005	154.97	143.79	148.41	179.12	86.3	9.57	1.08	10.64	6.94	36.59	65.36	55.02
2006	69.55	113.26	232.3	82.94	80.47	9.2	8.81	2.69	15.06	13.98	144.37	302.03
2007	256.38	283.93	87.75	130.76	33.85	19.76	13.82	21.07	14.35	26.47	83.83	199.86
2008	118.39	238.53	209.19	84.69	39.28	60.69	13.48	11.44	18.22	128.89	98.49	115.37
2009	200.08	215.73	189.98	185.17	181.76	80.22	4.95	18.51	15.62	56.68	178.41	278.69
2010	237.41	355.67	204.36	119.18	63.99	70.93	2.34	2.25	58.46	140.39	91.68	242.15
2011	406.38	389.18	617.81	438.84	458.13	238.22	79.22	136.56	444.98	584.29	745.29	701.9
2012	161.79	296	531.55	767.42	480.22	199.68	44.47	127.75	295.4	612.86	609.78	645.8
2013	471.7	389.11	696.27	649.92	401.06	63.43	12.18	88.27	462.74	448.29	684.6	770.05
2014	529.37	532.56	491.27	375.29	218.34	177.55	52.33	233.05	326.53	575.89	708.58	624.6
2015	392.6	482.94	435.52	640.6	398.6	199.91	30.08	16.36	255.1	670.02	680.96	628.72

2016	658.55	361.3	464.41	536.03	296.49	55.37	23.18	39.52	242.11	421.41	842.65	307.89

Appendix 3: Projected Temperature

Future Projected Averaged Monthly Temperature under RCP4.5 and RCP8.5 AR5 scenarios for 30 years from 2016

Projection Models: MIROC-ESM, CNRM-CM5, CanESM2, FGOALS-s2, BNU-ESM, MIROC5, GFDL-ESM2G, MIROC-ESM-CHEM, GFDL-ESM2M, MRI-CGCM3, and bcc-csm1-1.

Temperature in °C

2046	**RCP4.5 scenario**	**RCP8.5 scenario**
Jan	22.18	23.08
Feb	22.15	23.06
Mar	22.68	23.77
Apr	22.35	23.30
May	21.68	22.50
Jun	22.37	23.49
Jul	22.27	23.30
Aug	22.53	23.60
Sep	22.98	23.92
Oct	22.08	22.97
Nov	21.94	22.76
Dec	21.79	22.63

Appendix 4: Projected Precipitation

Future Projected Averaged Monthly Precipitation under RCP4.5 and RCP8.5 AR5 scenarios for 30 years from 2016

Projection Models: MIROC-ESM, CNRM-CM5, CanESM2, FGOALS-s2, BNU-ESM, MIROC5, GFDL-ESM2G, MIROC-ESM-CHEM, GFDL-ESM2M, MRI-CGCM3, and bcc-csm1-1.

Precipitation in mm

2046	RCP4.5 scenario	RCP8.5 scenario
Jan	125.80	103.21
Feb	44.45	47.61
Mar	143.33	130.37
Apr	123.11	111.74
May	66.54	45.19
Jun	18.10	15.02
Jul	36.97	33.93
Aug	15.38	7.36
Sep	55.87	54.97
Oct	107.50	101.15
Nov	110.20	112.95
Dec	45.99	44.01

Appendix 5: Nyaruguru Meteorological Station Coordinate in Meters

Station Names	Latitude	Longitude
Mata	451,169.329	9,716,845.340
Kibeho	448,732.441	9,709,437.201
Nshili	435,865.672	9,708,949.823
Runyombi	443,078.860	9,695,693.152
Cyahinda	457,602.713	,696,278.005
Muganza	440,057.119	9,705,928.082