SUITABILITY ASSESSMENT AND PROJECTED IMPACT OF CLIMATE CHANGE ON RICE YIELD IN TWO AGRO-ECOLOGICAL ZONES IN SOUTH-KIVU, DEMOCRATIC REPUBLIC OF CONGO

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DECLARATION

I, Muhindo Iragi Daniel hereby declare that the findings presented in this thesis report are my original work, and have never been submitted to Makerere University or any other institution of higher learning for the award of a degree.

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DEDICATION

This thesis is dedicated to:

My parents, Jean-Marie Muhindo Koko and Eugenie Sauli wa Bilinda, for their unconditioned love

My brothers Eddy, Johny, Conny, Eugène Muhindo and my cousins Blandine Sauli, Francine Sauli and Natacha Muhindo for their support

My beloved friend Néné Munene Neema for her presence in my life

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ACRONYMS

AgMIP: Agricultural Model Intercomparison and Improvement Project

DSRP: Document des stratégies de Réduction de la Pauvreté (Strategic document for poverty reduction)

DRC: Democratic Republic of Congo

FAO: Food and Agriculture Organization

ILWIS: Integrated Land and Water Information System

INERA: Institut National d'Etude et de Recherche Agronomiques

IPAPEL: Institut Provincial d'Agriculture, Pêche et Elevage

IPCC: Intergovernmental Panel on Climate Change

MAM: March to May (Season 2)

NEPAD : Nouveau partenariat pour le développement de l'Afrique (New partnership for African development)

SRES: Special Report on Emission Scenarios

SOND: September to December (Season 1)

ABSTRACT

Rice is one of the five most important staple foods in South-Kivu, with high and increasing demand. The gap between the demand and supply has led to increasing importation of rice in the region. Changes in climate are likely to further increase this gap. A study was conducted in South-Kivu to i) determine suitable areas for optimum rice growing and ii) determine the impact of historical and future climate on paddy rice yield in two agro-ecolgical zones (Kavumu and Luberizi) in the region. GIS-based multi-criteria analysis techniques were used in ArcGIS 10.2 to identify suitable areas for rice growth in the two locations while the Agricultural Production Systems Simulator Model (APSIM) was used to simulate the impact of historical and future climate change scenarios (Mid and end-century, Representative Concentration Pathways 4.5 and 8.5) on rice yield. The results obtained from this study indicate that Kavumu and Luberizi catchments cover 1744 ha and 16036 ha respectively and generally only a small portion of the two locations are at most moderately suitable for rice growth (7.51% and approximately 20% of the catchment in Kavumu and Luberizi, respectively). The marginally suitable class represented 72.88% and 36.09% of the catchment in Kavumu and Luberizi respectively. The most limiting factors to rice production in both catchments were temperature, nutrient retention capacity and erosion hazard. During the last 30 years (1980-2010) rice biomass significantly ($p<0.001$) declined in both catchments while rice grain yield remained stable ($p>0.05$) in Kavumu but significantly declined in Luberizi over time ($p<0.001$). Both rice biomass and grain yield are projected to increase with climate change in Kavumu, except for the end-century under RCP 8.5

while in Luberizi it is projected that there will be a decline in rice biomass and a slight increase in grain yield followed by a decline in the end-century under RCP 8.5.

CHAPTER ONE: INTRODUCTION

1.1 Background

Rice is a staple food for nearly half of the world's population and is also a key source of employment and income for rural people (FAO, 2003). It is rapidly becoming a major food crop in much of sub-Saharan Africa and is set to overtake maize, cassava, sorghum, and other cereals in the near future (Kihoro, 2013). Its demand is driven by population growth as well as by urbanization (Mati and Nyamai, 2009). In the Democratic Republic of Congo (DRC), the main staple food crops are cassava, maize, groundnuts, and rice. Rice is, however, produced in much smaller quantities and despite its high production potential, more than 90% of the rice consumed in the country is imported (Nsombo *et al.*, 2012). In South-Kivu, the dependence rate on neighboring countries (mostly Rwanda) for most food products is very high and is about 70% for rice (Vwima, 2014). To overcome this deficiency, scientists and planners have to work together in order to increase the area of cultivated rice and its productivity.

Rice can be grown as a dryland crop, but it is by origin and by preference of most cultivators mainly a wetland crop (Moormann and van Breemen, 1978). Wetlands are of value because they play an important role in maintaining environmental quality, supporting biodiversity and sustaining livelihoods through agriculture (McCartney *et al.*, 2005). However, increased use of wetlands should not be at the expense of future generations and should fulfill the concept of sustainability (Roger *et al.*, 1991).

Efficient management and optimum utilization of natural resources is essential for ensuring food supplies and sustainability in agricultural development (Dengiz, 2013). Continuous utilization of agriculture land in past decades, regardless of land suitability has caused much more destruction than provide the resources (FAO, 2007).

Land suitability is of great importance in the context of present day agriculture. It is the ability of a portion of land to tolerate the production of crops in a sustainable manner (Halder, 2013). The concept of sustainable agriculture or farming involves producing quality products in an environmentally benign, socially acceptable and economically efficient way (Addeo *et al.*, 2001). In order to comply with these principles of sustainable agriculture, one has to grow the crops in suitable areas (Nisar Ahamed *et al.*, 2000). Suitability has been defined as a function of crop requirements and land characteristics and it is a measure of how well the qualities of land units match the requirements of a particular form of land use (FAO, 1976).

Identifying and demarcating suitable areas for a given crop can be achieved by carrying out land suitability analysis. The latter requires the use of different kinds of data and information (soil, climate, land use, topography, etc.). The presence of various and multiple criteria makes land use suitability analysis increasingly complex (Duc, 2006). While conventional data processing systems have shown limitations in mapping and combining large datasets (MacDougall, 1975), the Geographic Information System (GIS) offers a flexible and powerful tool in data processing (Foote and Lynch, 1996). One of its most useful features is the ability to overlay different layers and maps. When combined with Multi-Criteria Analysis (MCA), GIS is a powerful approach to land suitability assessments. It enables computation of the criteria while MCA can be used to group them into suitability classes (Joerin *et al.*, 2001). GIS-based multi-criteria evaluation can be thought of as a process that combines and transforms spatial data (input) into a resultant decision (output) (Malczewski, 2004). It has received renewed attention within the context of GIS-based decision-making (Pereira and Duckstein, 1993) and has been used by several researchers (Al-Mashreki *et al.*, 2011; Kuria *et al.*, 2011; Kihoro *et al*., 2013; Dengiz, 2013) in land suitability studies.

Considering land suitability analysis is still not enough by its own to ensure sustainability of agricultural sector because other factors like climate change are also very important. Agriculture is always vulnerable to unfavorable weather events and climate conditions. It is the most sensitive sector to climate conditions, with both climate variability as well as climate change (Basak *et al.*, 2010).

Climate change, which is a consequence of changes in the atmospheric composition due mostly to anthropogenic increase in greenhouse gases leads to changes in the radiative balance of the earth and consequent alterations in temperature, circulation pattern and weather patterns (Saseendran *et al.*, 2000). It has many facets, including changes in long term trends in temperature and rainfall regimes as well as increasing variability in extreme events. The impacts of these changing conditions on agriculture are already being seen, yet there are still considerable gaps in the knowledge of how agricultural systems will be affected by both short- and long-term changes in climate (IPCC, 2007a).

Therefore, understanding the potential impact of climate change on agricultural systems is important for the development of appropriate strategies to adapt to and mitigate the likely outcomes on long-term food security (Nguyen, 2005).

It is expected that climate change will severely set back agricultural development in tropical countries, where an increasing share of the poorest and most vulnerable population resides (Wassmann and Dobermann, 2007). Currently, in DRC few studies have investigated the climate change impacts on agriculture in general and rice in particular. Therefore, although rice production has an enormous potential to increase food security in DRC and particularly in South-Kivu, it is still unclear how this potential will evolve under climate change (Nsombo *et al.*, 2012).

Impacts of climate change on crop productivity are generally assessed with crop models. Crop models were developed for simulations at field level and strongly emphasize biophysical factors, such as climate and soil conditions while considering a particular farm management (Reidsma *et al.*, 2010). The crop model for rice used in this study is the Agricultural Production Systems Simulator (APSIM) which is used worldwide.

1.2 Statement of the problem

Low rice production in the South-Kivu region has led to rice importations that exceed 6,048 tonnes per year only in Bukavu, the capital city of South-Kivu, yet South-Kivu has abundant unexploited natural resources that can be utilized to increase rice production (Ndaye, 2005). In the South-Kivu highlands, SIM Bushi identified 30,000 ha of wetlands while in the Ruzizi plain in the lowlands 80,000ha of arable soils are available. However, only 0.05% of these resources in the highland and 0.075% in the lowland are used for rice production (Buchekuderhwa, 2005). Few land evaluation studies have been done to determine how well the qualities of land units in the region match the crop requirements.

Low rice production in South-Kivu is likely to be exacerbated by climate variability already occurring in the region and future changes in climate which are projected to happen. Global warming induced changes in temperature and rainfall are already evident in many parts of the world, as well as in DRC (Ahmed, 1999). Nsombo *et al.* (2012), using the CSIRO model predicted rainfall reduction and temperature increment in DRC over the next 40 years. Though, South-Kivu province has been experiencing variations in monthly rainfall during the two last decades; no significant change in rainfall amount has been observed (Karume *et al.*, 2008). Associated impact of increasing temperature, changing rainfall pattern and intensity has led to reduced agricultural productivity and crop yield over the world (Ahmed and Fayyaz-ul-Hassan, 2011) and is likely to affect agricultural sector in South-Kivu. However, the nature of future changes in climate in South-Kivu is not yet well understood and how these changes are likely to affect agriculture, especially rice production, is not yet well documented.

1.3 Objectives of the study

1.3.1 Broad objective

The overall objective of the study was to contribute to a sustainable rice production through identifying suitable areas for optimum rice production and predicting the impact of climate change on rice yield in South-Kivu.

1.3.2 Specific objectives

The study aimed at:

(a) Determining suitable areas for optimum rice production in two agro-ecological zones in South-Kivu

(b) Assessing the trends of historical climate and its impact on rice yield in the two selected agro-ecological zones in South-Kivu

(c) Establishing the projected impact of climate change on paddy rice yield in the two selected agro-ecological zones in South-Kivu

1.4 Research questions

1. What are the suitable areas for optimum rice growing in the two agro-ecological zones?
2. Was rice yield in the two areas affected by historical climate?
3. Will rice yield in the two selected areas be affected by climate change in mid and end centuries?

1.5 Justification and significance of the study

South-Kivu, one of the Eastern provinces of DRC, faces multiple problems. The major problem is improving the lives of 71.3% of its population that suffers from extreme poverty (Aho *et al.*, 2009) and food insecurity. About 80% of the population survives on agriculture and related activities, therefore agricultural development will have to play a major role in improving food security while reducing poverty (Foster and Briceno-Garmendia, 2010).

Land suitability analysis is a prerequisite for agricultural development since it guides decisions on land utilization types for optimal use of the land resources (Oluwatosin, 2005) by providing the necessary information about the limitations and the possible opportunities for the land use under investigation based on the land capabilities (Rabia *et al.*, 2013). However, for a sustainable agricultural development, knowledge on possible impacts of climate change on agriculture is also essential. Despite technological advances such as improved crop varieties and irrigation systems, weather and climate are still key factors in agriculture productivity (Basak *et al.*, 2010).

For sustainable rice production, a crop-land suitability study and an investigation of the degree to which climate change is likely to impact on rice yields are therefore an absolute necessity in order to guide decision makers in selecting suitable land for rice cultivation and design adaptation strategies to climate change.

This study generated information provided in a publicly available format to enable land managers, scientists, and policy makers make informed decisions regarding land use, sustainable agriculture development and design adaptation measures for sustainable rice production. The downscaled climate information can also be used to assess the impact of climate change to other agricultural sectors. The generated data both climatic and production can be integrated in the national and regional data bases.

1.6 Conceptual framework

Figure 1 shows the conceptual framework for rice suitability assessment and impact of climate change on rice yield. Crop (rice) performance depends on temperature, rainfall, CO_2 concentration, solar radiation, soil properties, water availability and topography. The change in each of the aforementioned parameters is likely to yield different responses from the crop. This response varies with the level of suitability of the land to the crop. Under changing climate, temperature and rainfall are likely to increase in Eastern DRC. This study intended to determine rice response induced by those changes assuming that all the other parameters remained the same. This was evaluated using APSIM. Knowledge on both rice suitability assessment and impact of climate change on rice yield is necessary for policy advocacy and adaptation measures planning.

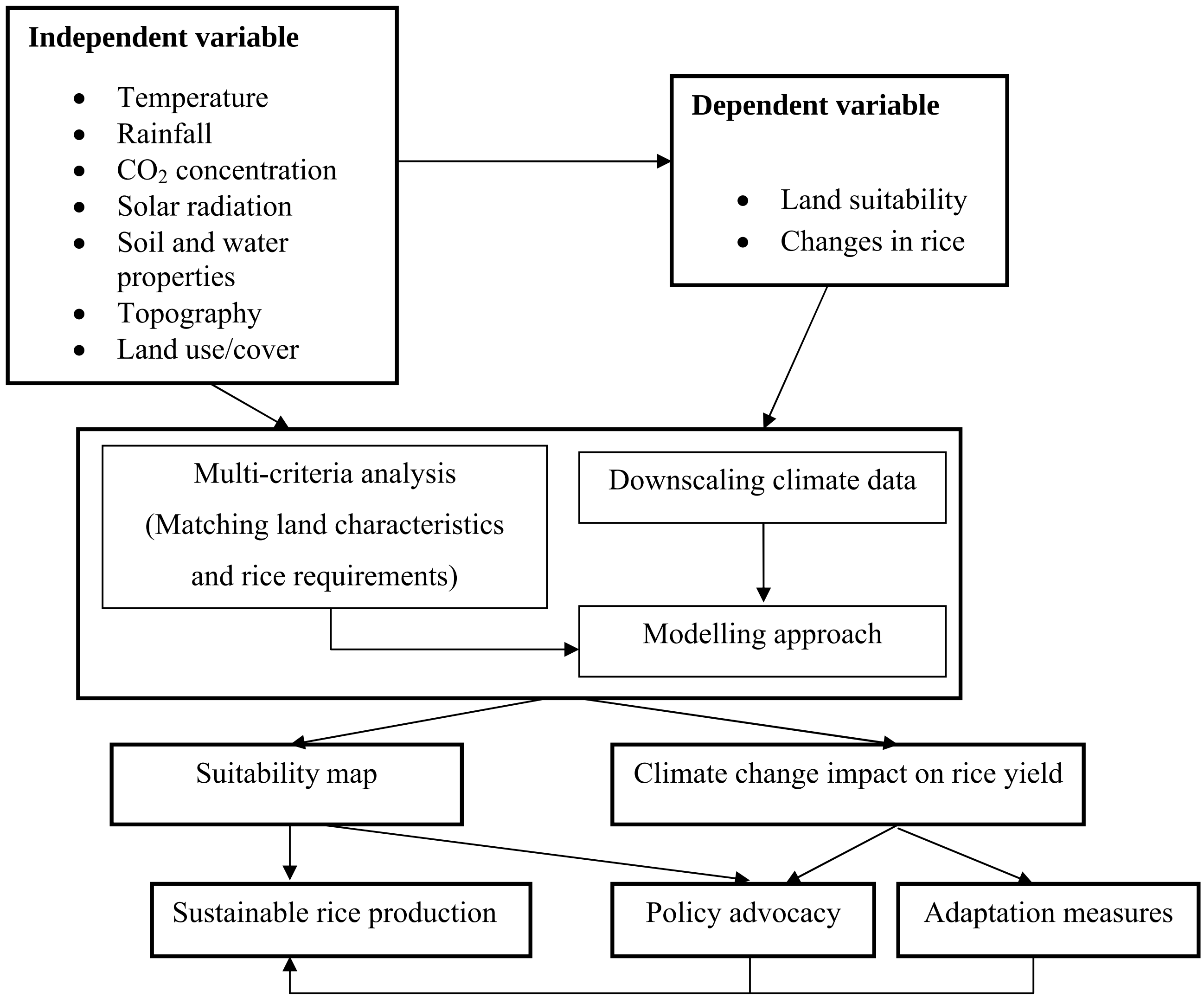


Figure 1: Conceptual framework

CHAPTER TWO: LITERATURE REVIEW

2.1 Socio-economic importance of rice

The relative importance of rice in Africa seemed for a number years to be minimal compared to other developing countries all over the world mainly because of low production (Westphal *et al.*, 1985). Today rice plays a significant role in ensuring food security in the world in general and in Africa in particular. It is also a source of income for farmers and sellers (FAO, 2003). In DRC, rice is one of the 5 major crops (Nsombo *et al.*, 2012). In 2000, 14% of the farmers in the country representing at that time 0.92 million people were rice growers, most of whom relied on this crop as a major source of income (NEPAD, 2006).

Currently, more farmers are interested in rice cultivation and its demand is increasing due to urbanization, population growth and change in eating habits. In South-Kivu, rice is a profitable crop. It is mainly used as food and as a raw material in processing industries namely the breweries and pharmaceutical plants (De Failly, 2000). From 1975 to 2000, the consumption of rice locally produced increased by about 270% (Tollens, 2004). Unfortunately, its production is still very insufficient and can't therefore match the demand (Bucekuderhwa, 2005). This is exacerbated by the poor state of roads network, which does not allow rice farmers to easily access the markets. For the last four decades the gap between the demand and the supply has been covered through rice importation. From 1975 to 2000 the rice imported increased by about 240% in the capital Kinshasa (Tollens, 2004).

2.2 Rice production in South-Kivu

Rice cultivation existed in DRC since 1840 and was introduced by the Arabs. However, its expansion only started in 1935 when several local and foreign varieties were tested and disseminated by INEAC (Institute of Agronomic Sciences in Congo) in the rural areas. Rice cultivation is 96% rainfed and is mainly practiced in Bandundu, Bas-congo, Kasaï-Oriental, Equateur and Kivu provinces (Blench, 2013). In Kivu, rice cultivation is practiced in the territories of Beni, Lubero, Rutshuru, Masisi, Walikale, Mwenga, Shabunda, Kalehe, Walungu, Fizi, Kindu, Kabambare, Kasongo, Kibombo, Pangi, Lubutu, Uvira and Kabare. Paddy rice is most common in Kabare and Uvira in South-Kivu. The rice here is transplanted (Blench, 2013) and land preparation is carried out by tractors, using animal traction [ox-ploughs] or by hand. However, manual labor, using hoes, is most common especially in Kabare. Even where tractors are used, much of the subsequent labor has to be completed by hand. All the other activities, including land leveling, channel clearing, transplanting, harvesting and threshing are carried out manually (Blench, 2013).

Since many of the farmers do not live near their fields, a system of field guarding has been instituted, whereby individuals are paid to oversee the fields, to ensure no problems arise. Birds feeding on the crops are a problem in the last two months to maturity, and children or young adults must be paid as bird-scarers (Blench, 2013).

Rights to the land are generally obtained through inheritance, customary land-allocations from chiefs, or concessions from government officials (Vlassenroot and Huggins, 2005).

Many rice farmers, however, hire the land they cultivate and the contracts are simple annual cash contracts with the lessee paying prior to working the land (Blench, 2013).

Figure 2 below shows the production trends of rice in South-Kivu from 1992 to 2012. Generally, the total production followed an increasing trend from 1992 to 2012. It however, declined in 1996, 1998 and from 2001 to 2005 due to insecurity and wars mostly in the eastern part of DRC. An increasing though fluctuating trend occurred from 2006 to 2012. In 2012, the total production reached 114,605 tonnes.

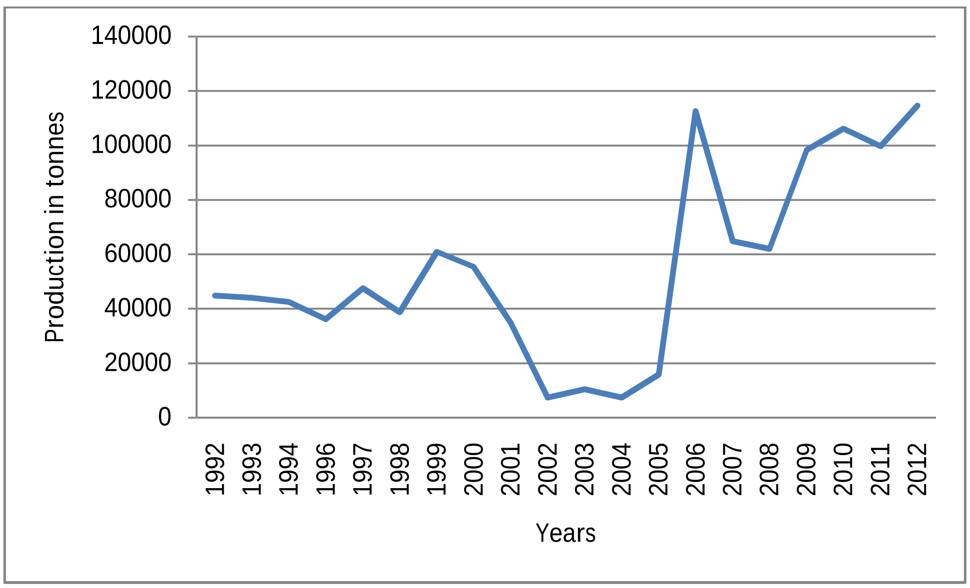


Figure 2: Production trend of rice in South-Kivu from 1992 to 2012 (IPAPEL, 2014)

Most of the rice is produced in Shabunda (71.96%), Mwenga (13.25%) and Uvira (10.37%) (IPAPEL, 2014). Rice from Shabunda and Mwenga is rainfed and never reaches the city because of insecurity and the poor state of the roads. In Uvira, however, rice is irrigated and much of the production is sold across the border to buyers mostly from Rwanda and Burundi (Blench, 2013). A considerable part (1250 tonnes per year) is bought by the local brewery BRALIMA. The remaining part is unfortunately not enough to satisfy the population demand, thereby leading to importation (De Failly, 2000).

2.3 Agroclimatic zones and rice ecosystems

The suitability of land for various crops is determined by climate and weather variables (agroclimatic zones), landscape moisture regimes (physio-hydrographic positions), and soil characteristics (Balasubramanian *et al.*, 2007). Rice being a tropical and sub-tropical crop is normally grown at a fairly high temperature and high rainfall regime, ranging from 20° to 40°C and 1250mm to 2000mm of annual rainfall. Flat fields having low slopes with smooth surfaces are better for rice cultivation as this facilitates even and equal distribution of water. Clay, silt clay, silt clay loam, textures of soil are best for paddy/rice crop. Slightly acid soils having a pH value of 6 to 7 are better for paddy cultivation. However, it has been found to grow under a wide range of pH varying from 4 to 8 (Samanta *et al.*, 2011). Rice can grow in a variety of ecosystems varying from drylands to wetlands (Balasubramanian *et al.*, 2007).

Dryland rice also known as‘‘upland’’or‘‘pluvial’’rice is cultivated on level and/or sloping lands (Sie, 1991). Flooding is rare in this ecosystem, and dry land rice depends solely on rainfall. Dry land rice is generally a subsistence crop in Africa and of critical importance for the local food security of poor communities that do not have access to wetland fields (Balasubramanian *et al.*, 2007).

Unlike the dry land ecosystem, rice fields in the wetland ecosystem are flooded during the growing season. There are three types of wetland rice ecosystems (rainfed wetland, deepwater, and irrigated) as determined by the surface-water regime. An ecosystem is considered to be a rainfed wetland when the water supply to the crops is from rainfall and groundwater. Rainfed wetland rice is grown in flat to slightly sloping fields usually in valleys (Balasubramanian *et al.*, 2007). Rainfed wetlands are characterized by a lack of water control, with droughts and floods being potential problems (Hatibu *et al.*, 2000; McLean *et al.*, 2002).

In contrast, in the deep water ecosystem, most of the water in the fields is from the lateral flow of water onto the land. Rice plants in deepwater ecosystems are adapted to increasing water depths of one meter or more for durations of 10 days to 5 months. They must have the ability to elongate rapidly to stay above the water surface (McLean *et al.*, 2002).

In the irrigated wetland ecosystem, a significant part of the water supply is from irrigation. Irrigated rice is grown in fields with assured irrigation for one or more crops per year. Usually, farmers try to maintain 0.05 to 0.1 m of water in rice fields. Irrigated rice areas are concentrated mostly in the humid, sub-humid, semiarid, and high-altitude tropics of the continent. Dams across rivers, diversion of water from rivers, or tube wells provide water for irrigation (Balasubramanian *et al.*, 2007).

2.4 Suitability assessment

2.4.1 Role of GIS and Remote Sensing in land suitability assessment

GIS is conventionally seen as a set of tools for the input, storage and retrieval, manipulation and analysis, and output of spatial data (Marble *et al.* 1984, Malczewski, 2004). It has the ability to perform numerous tasks utilizing both spatial and attribute data stored in it and to integrate a variety of geographic technologies like GPS, Remote Sensing, Computer Aided Design, Automated Mapping and Facilities Management and other related technologies (Foote and Lynch 1996).

In general one of the most important uses of GIS is the land use suitability mapping and analysis (Abu Bakar, 2007). Combined with remote sensing, it is a powerful tool to integrate and interpret real world situation in most realistic and transparent way; it also has the ability to locate potential new cropland sites. Remote sensing provides the information about the various spatial and attribute stored in it. It can provide information like land use/cover, topography and drainage density. (Leingsakul *et al.*, 1993).

2.4.2 GIS approach for land suitability

Land Suitability Analysis (LSA) is a GIS-based process applied to determine the suitability of a specific area for considered use (Jafari and Zaredar, 2010). It is different from land capability which is the ability of a given natural land to perform as it is. For example the capability of the land may be forest area but the land may be suitable for annual crops (Semeneh, 2012). The main objective of the land suitability analysis is the prediction of the inherent capacity of a land unit to support a specific land use for a long period of time without deterioration, in order to minimize the socio-economic and environmental costs (Prakash, 2003).

2.4.3 Multi-criteria analysis

Agricultural land suitability is an interdisciplinary approach. It involves integration of data from various domains and sources like soil science to social science, meteorology to management science. All these major streams can be considered as separate groups and each group can have various parameters (criteria) in itself. However all the criteria are not equally important, each criterion will contribute towards the suitability at different levels. The relative degree of contribution of various criteria can be addressed well when they are grouped into various groups and organized at various hierarchies (Ceballos-Silva and Lopez-Blanco, 2003).

Agricultural land suitability also involves major decisions at various levels starting from choosing a major land use type, selection of criteria, organization of the criteria, deciding suitability limits for each class of the criteria, deciding the preferences (qualitative and quantitative). However, the relative importance of these parameters can be well evaluated to determine the suitability by multi-criteria techniques (Ceballos-Silva and Lopez-Blanco, 2003).

Multi-criteria evaluation or analysis is an effective tool for multiple criteria decision-making issues (Malczewski, 2006) and aims to investigate a number of choice possibilities in light of not only multiple criteria but also multiple objectives (Carver, 1991). It has been developed to improve spatial decision making when a set of alternatives need to be evaluated on the basis of conflicting and incommensurate criteria (Jankowski *et al.* 2001, Mustafa *et al.*, 2011). Several researches on land suitability assessment (Joerin *et al.*, 2001; Shari, 2004; Al-Mashreki *et al.*, 2011; Halder, 2013) have been conducted using multi-criteria techniques; many scholars used it particularly in suitability assessment for rice cultivation studies (Gumma *et al.*, 2009; Kuria *et al.*, 2011; Samantha *et al.*, 2011; Hussain, 2012 ; Dengiz, 2013 ; Halder, 2013 ; Kihoro *et al*., 2013).

2.5 Climate change and rice production

2.5.1 Climate change and its evidence

Global warming, on the one hand, is the phenomenon in which greenhouse gas (GHGs), such as CO_2, CH_4 and N_2O, act as a shield and trap solar heat and keep it from escaping into outer space, thereby increasing Earth's mean surface temperature (Kang and Banga, 2013). Climate change, on the other hand, is defined as an overall shift in climate conditions such as mean maximum or minimum temperature and average total rainfall in a given region over a long period (Rosenzweig and Hillel, 2008). It can also be defined as a statistically significant variation in either the mean state of the climate or in its, variability, persisting for an extended period (typically decades or longer). It may be due to natural internal processes or external forcing, or to persistent anthropogenic changes in the composition of atmosphere or in land use (IPCC, 2001).

Climate change as the consequence of global warming and depletion of the ozone layer is already being experienced across the world. Carbon dioxide (CO_2) concentrations in the atmosphere are rising, as are temperatures (IPCC, 2007a). The global atmospheric concentration of carbon dioxide, a GHG largely responsible for global warming, has increased from a pre-industrial value of about 280 ppm to 387 ppm in 2010. Similarly, the global atmospheric concentration of methane and nitrous oxides, other important GHGs, has also increased considerably (IPCC, 2007 b). In the past 100 years (1906-2005), the global surface air temperature increased by 0.74°C, ranging from 0.56 to 0.92°C (IPCC 2007a).Under its baseline projection, the IPCC projects further global warming of 1.1 to 6.2 °C by the end of this century (IPCC, 2007c). These changes in climate volatility are likely to be particularly important for agricultural systems, which can be quite sensitive to such extremes (White *et al.*, 2006).

In the exploitation of natural resources, man has altered the composition of the atmosphere and intervened in the earth's climate by emissions and by continued changes in the distribution of land use and natural vegetation. Man-made greenhouse gas emissions as a result of industrialization and urbanization have made significant contributions to global warming and further changes in the global climate (Gohari *et al.*, 2013).

2.5.2 Impact of climate change on rice production

Generally climate and weather conditions determine plant growth and yield formation, depending on the plant characteristics. Plants normally are adapted more or less to the climatic conditions of their natural growing areas (Wild, 2003). Climate directly influences the physiological processes that affect all vegetation as well as the rice plant's growth, development and grain formation. Climate change will aggravate a variety of stresses for rice plants, namely heat, drought, salinity, and submergence (Wassmann *et al.*, 2009).

Studies suggest that the temperature increases, rising sea levels and changes in rainfall patterns and distribution expected as a result of global climate change could lead to substantial modifications in land and water resources for rice production as well as in the productivity of rice crops grown in different parts of the world (Nguyen, 2005).

2.5.2.1 Temperature increase

Critically low and/or high temperatures define the environment where the phenological cycle of the rice plant can be completed. Critical temperature thresholds are (1) low temperatures around 15°C from the seedling stage to panicle initiation and (2) low temperatures around 20°C or high temperatures around 35°C at flowering which could induce sterility during pollination (about 80 days after planting) (Yoshida, 1976).

Temperature regimes greatly influence not only the growth duration, but also the growth pattern and the productivity of rice crops. Extreme temperatures – whether low or high – cause injury to the rice plant. Temperatures beyond critical thresholds not only reduce the growth duration of the rice crop, they also increase spikelet sterility, reduce grain-filling duration, and enhance respiratory losses, resulting in lower yields and lower-quality rice grain (Bachelet and Gay, 1993; Matsui *et al.*, 1997; Matthews and Wassmann, 2003).

Rice is relatively more tolerant to high temperatures during the vegetative phase but highly susceptible during the reproductive phase, particularly at the flowering stage (Stigter and Winarto, 2013). In tropical regions, high temperatures are a constraint to rice production. The most damaging effect is on grain sterility; just 1 or 2 hours of high temperature at anthesis (about 9 days before heading and at heading) result in a large percentage of grain sterility (Nguyen, 2005).

Temperature increases in subtropical and temperate climate areas may have a positive or negative effect on rice crops, depending on the location (Ferrero and Nguyen, 2004). For example, temperature increase would improve the crop establishment of rice in Kavumu, where cool weather usually causes poor crop establishment.

2.5.2.2 Carbon dioxide

For every 75 ppm increase in carbone dioxide (CO_2) concentration, rice yields will increase by 0.5 t/ha (Vaghefi *et al.*, 2011; Stigter and Winarto, 2013). Increased concentration of CO_2 in the atmosphere has a positive effect on crop growth and yield, provided that microsporogenesis, flowering, and grain-filling are not disrupted by increase in temperature (Stigter and Winarto, 2013). Strain (1985) stated that the net effect of CO_2 on plant reproduction is to accelerate all phenological events from anthesis to seed maturation.

A number of studies examined the effects of CO_2 concentration on competing assemblages of different species and it was found out that the competitive ability of the C_3 species improved in assemblages grown in enriched CO_2 as compared with ambient level atmospheres (Bazzaz, 1990; Bowes, 1993; Ehleringer and Monson, 1993). In the case of rice cultivation, this would mean that rice, which is a C_3 plant, would compete advantageously with common weeds such as *Echinochloa* spp. which have the C_4 pathway (Patterson and Flint, 1990).

2.5.2.3 Changes in the pattern of precipitation

Floods are the most important constraint to rice production in low-lying areas. Most rice varieties for rain-fed lowland, irrigated and deep-water ecosystems can stand complete submergence for at least 6 days before 50 percent of them die (Nguyen, 2005). However, the mortality rate becomes 100 percent when submergence lasts 14 days. Floods also cause indirect damage to rice production through the destruction of property and farmers' production means, as well as infrastructure supporting rice production (e.g. dams, dikes and roads) (Nguyen, 2005). The changes in the pattern of rainfall distribution may lead to a more frequent occurrence of intense floods and drought in different parts of the world (Depledge, 2002).

2.5.2.4 Rising sea levels

The rising sea levels expected under global climate changes would definitely increase the size of land areas that are influenced by tidal waves in the low-lying deltas of the major river systems (Nguyen, 2005). Yields of rice planted in tidal-affected lands, however, are normally lower than that in lowlands that are not influenced by tidal waves. This is due to the salinity in the soil (tidal waves contaminate water and soil with the salt in the seawater) (Ponnamperuma and Bandyopadhya, 1980). The increasing threat of salinity is an important issue (Stigter and Winarto, 2013). Most rice varieties are severely injured in submerged soil culture at an electrical conductivity (EC) of 8–10 mmho/cm at 25°C (Ponnamperuma and Bandyopadhya, 1980).

2.5.3 Climate change models

Various studies have been conducted to identify global and regional change in climate and to separate the signal of human influence from the background noise of natural climate variability (Mitchell *et al.*, 2001; Ramanathan and Carmichael, 2008; Hasselmann, 2013; Santer *et al.*, 2013). General Circulation Models (GCMs) are tools used to assess global scale climate change. GCMs are numerically coupled models that represent various aspects of the earth system including the atmosphere, oceans, land, land surfaces, and sea-ice (Ramirez-Villegas and Jarvis, 2010). GCMs are based on physical laws of conservation of mass, energy, and momentum and are used to downscale climate data and predict climate change by simulating the effects of predicted concentrations of GHGs and aerosols in the atmosphere (Randall *et al.*, 2007; Dowling, 2013).

2.5.4 Climate change scenarios

To improve understanding of the complex interactions of the climate system, ecosystems, and human activities and conditions, the research community develops and uses scenarios. These scenarios provide plausible descriptions of how the future might unfold in several key areas -socioeconomic, technological and environmental conditions, emissions of greenhouse gases and aerosols, and climate (Moss *et al.*, 2010).

The IPCC Fifth Assessment Report (AR5) has introduced a new way of developing scenarios. These scenarios span the range of plausible radiative forcing scenarios, and are called representative concentration pathways (RCPs) (Chaturvedi *et al.*, 2012). RCPs are prescribed pathways for greenhouse gas and aerosol concentrations, together with land use change, that are consistent with a set of broad climate outcomes used by the climate modeling community. The pathways are characterized by the radiative forcing produced by the end of the 21st century. Radiative forcing is the extra heat the lower atmosphere will retain as a result of additional greenhouse gases, measured in Watts per square metre (W/m^2).

With these new scenarios, the complexity of humanity's possible future emissions has been reduced to just four representative pathways. RCPs take into account the impact of atmospheric concentrations of carbon dioxide and other greenhouse gases and aerosols (such as sulfate and soot). Each of the RCPs covers the 1850–2100 period. They include one mitigation scenario leading to a very low forcing level (RCP2.6), two medium stabilisation scenarios (RCP4.5 and RCP6) and one very high baseline emission scenario (RCP8.5) (Riahi *et al.*, 2007).

The 8.5 pathway arises from little effort to reduce emissions and represents a failure to curb warming by 2100. It is similar to the highest-emission scenario (A1FI) in the IPCC Fourth Assessment Report (AR4) (Riahi *et al.*, 2007). The 6.0 pathway stabilizes total radiative forcing shortly after 2100 by the application of a range of technologies and strategies for reducing greenhouse gas emissions (Masui *et al.*, 2011). RCP4.5 is similar to the lowest-emission scenario (B1) assessed in the IPCC AR4 (Thomson *et al.*, 2011). RCP 2.6 is the most ambitious pathway. It sees emissions peak early, then fall due to active removal of atmospheric carbon dioxide. This pathway is also referred to as RCP3PD (representing the mid-century peak radiative forcing of ~3W/m² followed by a decline). RCP 2.6 needs early participation from all the main emitters, including those in developing countries. It has no counterpart in IPCC AR4 (Van Vuuren *et al.*, 2011). The equivalent atmospheric CO_2 concentrations of the four RCPs by 2100 are listed in table 2.

Table 1: Approximate CO2 equivalent concentrations in ppm by 2100 of the four RCPs

RCP	Approximate CO_2 equivalent concentrations by 2100 (ppm)
8.5	>1370
6	850
4.5	650
2.6	490

Source : IGBP, 2010.

According to Moss *et al.* (2010), there are three main reasons for developing a new set of scenarios. First of all, the SRES scenarios only considered developments in the absence of climate policy. Since then, a considerable amount of literature has emerged that looks into mitigation scenarios, responding to a shift in policy attention away from the need for climate policy to evaluate the costs and benefits of different types of climate policy (Fisher *et al.*, 2007; Edenhofer *et al.*, 2010). Secondly, new advances in climate models have led to a need for more detailed scenario information than that provided by SRES: aerosol emissions, geographically explicit descriptions of land use and emissions and detailed specification of emissions by source type. Thirdly, there is a need for closer collaboration between the different disciplines involved in climate scenario formulation and use to allow for consistent usage of scenarios for the different objectives and methods of the modeling. This collaboration has been built into the design process for the new scenarios (Imogen *et al.*, 2013).

The RCPs span a wider range of possibilities than the SRES marker scenarios used in the modeling for the IPCC 3rd and 4th Assessment. RCPs start with atmospheric concentrations of greenhouse gases rather than socioeconomic processes. This is important because every modeling step from a socioeconomic scenario to climate change impacts adds uncertainty. By starting with concentrations, there are fewer steps to impacts and therefore less cumulative uncertainty in impact assessments. This way uncertainty is shared more evenly among the various components. The RCPs are not a complete package of socioeconomic, emission and climate projections. Rather, they are internally consistent sets of projections of the components of radiative forcing that are used in subsequent phases of climate modeling (Imogen *et al.*, 2013).

2.5.5 Assessment of climate change induced impacts on crop yield

Several models are available to assess the impact of climate change on crop yield including AquaCrop, DSSAT, APSIM and CropSyst. However, for the purpose of this study, only an overview of APSIM which was used in the study is given below.

2.5.5.1 An overview of APSIM

The APSIM is a dynamic daily time-step model that combines biophysical and management modules within a central engine to simulate cropping systems (Gaydon *et al.*, 2012). It was developed in 1991 through the collaboration between two groups, the Commonwealth Scientific Industrial Research Organisation (CSIRO) and the Agricultural Production Systems Research Unit (APSRU). The development team grew from the initial 2 programmers and 6 scientists to 6 programmers and software engineers and 12 scientists in 2003 (Keating *et al.*, 2003).

The APSIM farming systems model has a proven track record in modeling the performance of diverse farming systems, rotations, fallowing, environmental dynamics and crops including rice (Gaydon *et al.,* 2009). It was developed primarily as a research tool to investigate on-farm management practices especially where outcomes are affected by variable climatic conditions. Its use has been extended to looking at modifying farm practices and to include analysis of natural resource management issues including salinity and solute movement, climate risk studies, and climate change scenarios (Holzworth *et al.*, 2006).

The suitability of APSIM to predictive modeling is demonstrated by the following attributes: (1) the ability to simulate important phenomena due to improved representation of certain aspects of the cropping system; (2) advanced setup and ease in which routines from different modules can be combined; and (3) support teams which assist in improving and testing the various modules (McCown *et al.*, 1996).

The APSIM modeling framework is made up of a set of biophysical modules that simulate biological and physical processes in farming systems, a set of management modules that allow the user to specify the intended management rules that characterize the scenario being simulated and that control the conduct of the simulation, various modules to facilitate data input and output to and from the simulation, a simulation engine that drives the simulation process and controls all messages passing between the independent modules (Keating *et al.*, 2003).

An APSIM simulation is configured by specifying the modules to be used in the simulation and the data sets required by those modules. APSIM modules typically require initialization data and temporal data as the simulation proceeds. Initialization data is usually categorized into generic data (which defines the module for all simulations) and simulation specific parameter data such as site, cultivar and management characteristics modules (Keating *et al.*, 2003). Typical site parameters are soil characteristics for soil modules, climate measurements for meteorological modules, soil surface characteristics and surface residue definition. Management is specified using a simple language to define a set of rules, calculations and messages to modules that are used during the simulation modules (Keating *et al.*, 2003).

CHAPTER THREE: MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Location

This study was conducted in the South-Kivu province, Eastern DRC, specifically in two catchments namely Luberizi in the lowlands located in the Ruzizi plain in the territory of Uvira (altitude: 773- 1000m, latitude: 2°21’-3°32’S, longitude: 28°35’-29°56’E) and Kavumu in the highlands located in the territory of Kabare (altitude: 1500m, latitude: 2°15’-2°38’S, longitude: 28°12’-28°42’E). The choice of these catchments was motivated by their accessibility and the major role they play as sources of locally produced rice within the province. One was chosen in the lowland and another one in the highland to compare the impact of climate change on rice yield in two different agro-ecological zones.

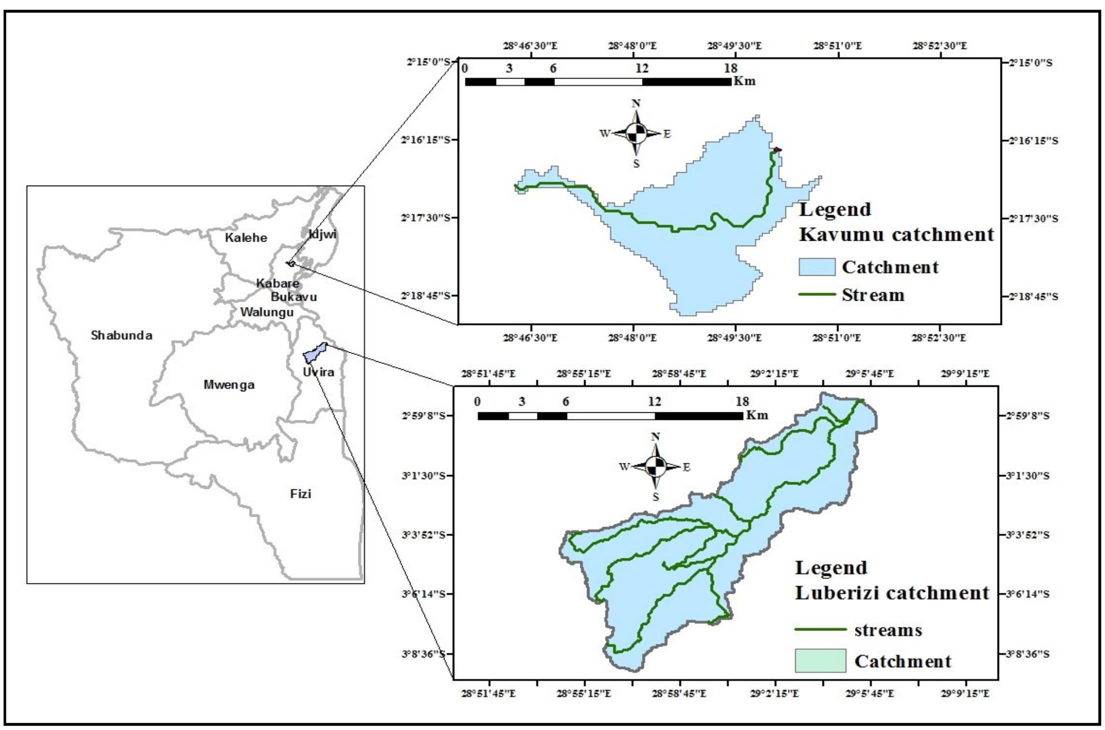


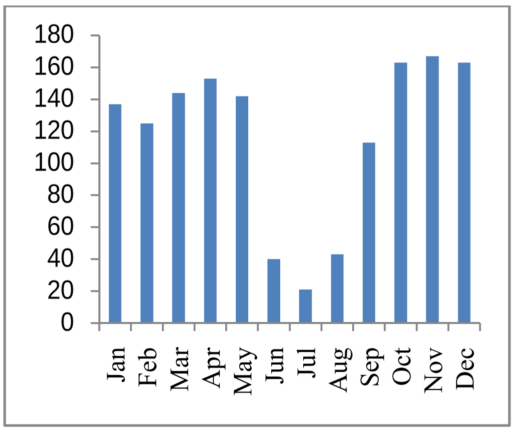
Figure 3: Location of the study area

3.1.2 Climate

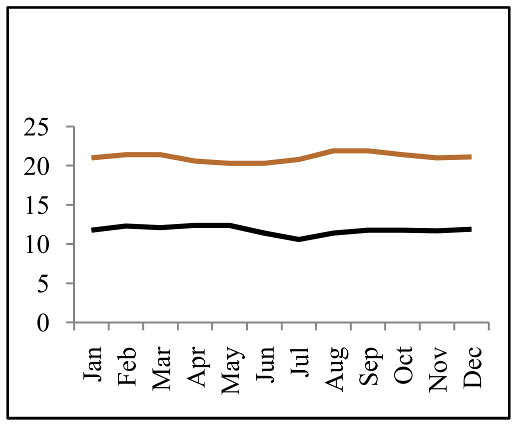
South-Kivu has two types of climate: an equatorial climate with rains throughout the year and a tropical climate with a rainy and a dry season (Aho *et al.*, 2009). The territory of Kabare has a high altitude tropical climate falling within the Aw3 type with the driest month having precipitation less than 60 mm and also less than (100 − [total annual precipitation {mm}/25]), according to Koppen classification. It has two seasons. The dry season takes 3 months from June to September and is hot with low and poorly distributed rainfall while the rainy season lasts 9 months with very high precipitation. However, the variability in climate disturbs the distribution of precipitation even during the rainy season. Precipitation generally increases with altitude while temperatures decrease with altitude (INERA, 2012). In the territory of Uvira, specifically in the Ruzizi plain, the climate is semi-arid of type Aw4 according to Koppen classification, characterized by 4 months of dry period during which precipitation is usually below 50mm. Precipitation oscillates between 900 and 1000 mm/yr during the rainy months (Burnotte, 1949), with March being the wettest month with mean rainfall of 140-160 mm in the plain and 180-200 mm in the hills, depending on the site. The dry season usually begins in the second half of May and persists until the end of September.

The averages of monthly precipitation (mm), maximum and minimum temperature (°C) in Kavumu and Luberizi from 1980 up to 2010 are shown in figures 4 and 5. The average total rainfall in Kavumu is 1411 mm per year (varying between 1134 and 1688 mm over the last 30 years). The dry season runs from June to September, with July being the driest month. The rainy season also lasts for 9 months, with November being the wettest month.

The average daily minimum temperature is 11.8°C while the average daily maximum temperature is 21.1°C. In Luberizi, the average total rainfall is 978 mm per year (varying between 754 and 1201 mm over the last 30 years). The dry season runs from June to September, with July being the driest month. The rainy season also lasts 9 months, with March being the wettest month. The average daily maximum temperature is 29.3°C and the average daily minimum temperature is 18.6°C.

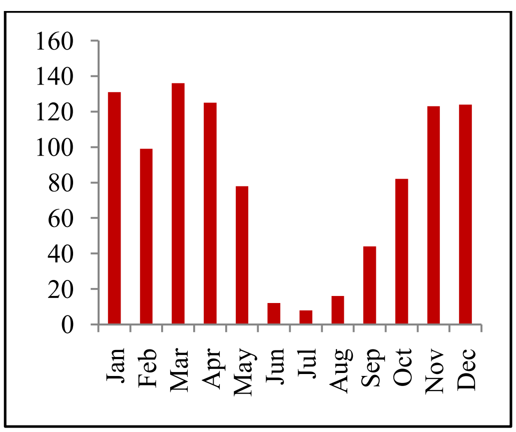


(a)

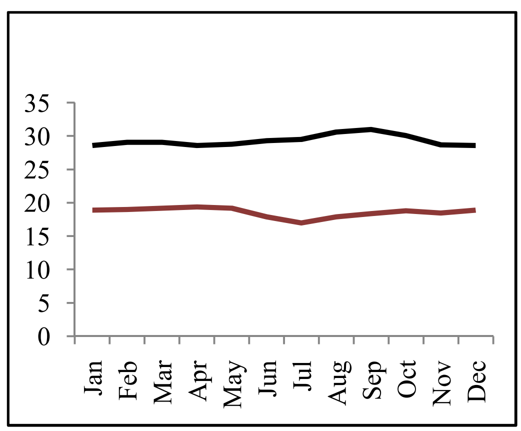


(b)

Figure 4: (a)Average rainfall, (b) maximum and minimum temperatures in Kavumu



(a)



(b)

Figure 5: (a)Average rainfall, (b) maximum and minimum temperatures in Luberizi

Source: AgMerra database

3.1.3 Soils

The territory of Kabare in general has clayey soils (DSRP, 2005). Kavumu catchment is dominated by humic ferralsols (figure 6). Ferralsols are the leached and deeply weathered red or yellow soils of the humid tropics. They have stable microaggregates, good porosity, permeability and infiltration. Their soil pH, base saturation and effective cation exchange capacity are however low. There is high retention by the soil colloids of applied phosphate leading to reduction in its immediate availability to crops (FAO, 2006).

The territory of Uvira has sandy to sandy clay soils, with variable levels of clay and generally poor organic matter and phosphorus content (Burnotte, 1949; DSRP, 2005). Ferrasols, acrisols and Phaeozem soils are found in Luberizi catchment; ferrasols covering almost 90% of the catchment (figure 6).

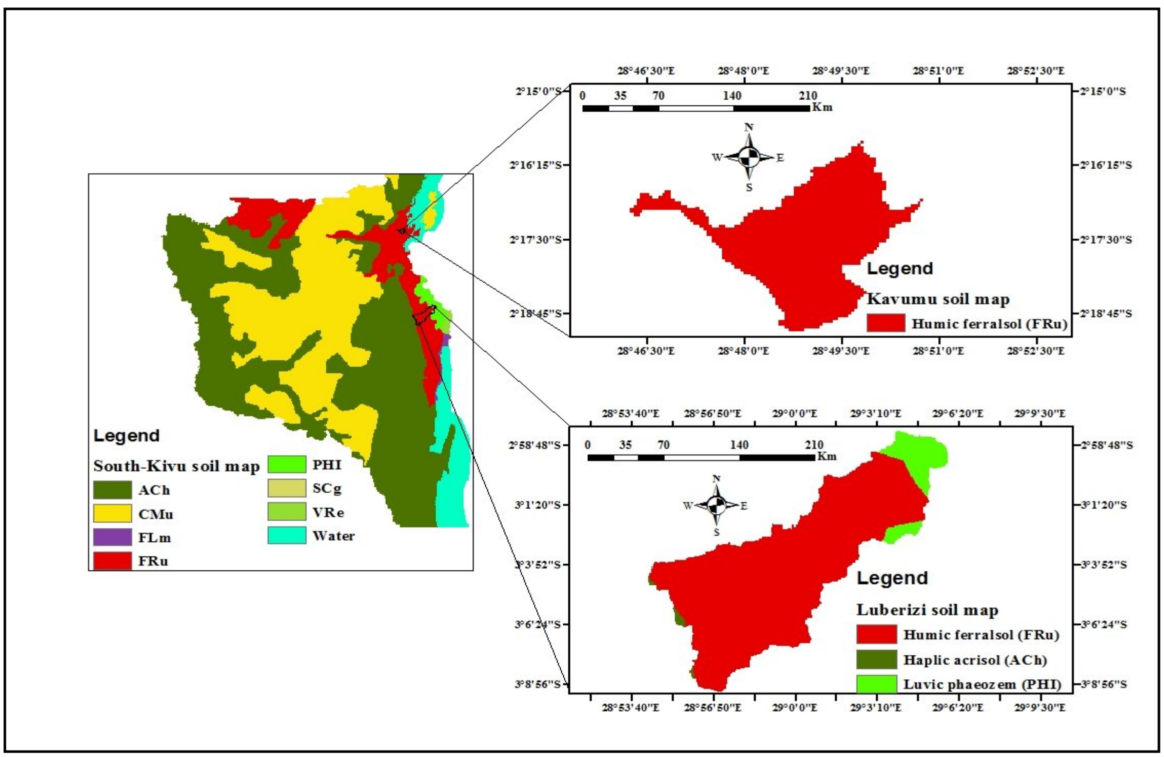


Figure 6: Soil map of Kavumu and Luberizi catchments (source: SOTER database)

3.1.4 Topography

The topography in South-Kivu varies depending on the location. The East of the province where Kabare is located is very mountainous and different from the center and the west of the province where the high and low plateaus are found. The high topography characterizing the eastern part of the province is expected to be Mitumba chain extension whose altitude exceeds 3000 m at some points. However, low topographies are found in the Ruzizi plain in the territory of Uvira where Luberizi catchment is located (DSRP, 2005).

3.1.5 Hydrography

The hydrographic network in South-Kivu is composed mainly of Lake Kivu, river Ruzizi and Lake Tanganyika. River Ruzizi links Lake Kivu to Lake Tanganyika and passes through the entire Ruzizi plain from the North to the South (Burnotte, 1949). It has 7 tributaries, among them Luvungi, Luyubu, Sange, Runingu, Kiliba, Kawizi and Luberizi. Luberizi River is the main river supplying water in the Luberizi catchment and is suitable for irrigation (Burnotte, 1949). Kavumu catchment is supplied with water through one of the river Lwiro’s tributaries. River Lwiro flows into Lake Kivu and is one of the 6 main rivers of Kabare territory (Basimine *et al.*, 2014).

3.2 Research approach

3.2.1 Determination of potential areas for paddy rice production within the catchments of Kavumu and Luberizi wetland

Wetlands were considered as potential areas for rice growth. The area suitable for rice production within the two catchments was determined matching the land quality with the rice requirements after demarcation of the two wetlands and their catchments. The two wetlands were detected through the analysis of the 5th September 2005 satellite image (p173r062) covering the study area. The image was downloaded from Landsat.org website. It was then processed using Integrated Land and Water Information System (ILWIS) version 3.3. Shuttle radar topography mission (SRTM) ~90m digital elevation model (DEM) was analyzed in ArcGIS 10.2 using Soil and Water Assessment Tool (SWAT) to delineate the two catchments of interest. The land characteristics used in this study involved biophysical input data namely climate, soil, water and topography.

Data on soil properties was derived from the SOTER database. They included pH, Cation Exchange Capacity (CEC), total organic carbon (TOC), total nitrogen (TN) and potassium (K) and texture. Raster maps were generated for each of the aforementioned parameters. Topography information was obtained from the SRTM~90mDEM, and was used to generate the slope map in ArcGIS 10.2. Temperature and rainfall are two climatic factors which have a favorable and in some cases unfavorable influence on the development, growth and yield of rice and were therefore considered as key climatic parameters in the study (Samanta *et al.*, 2011). Raster datasets were generated by interpolation in Arc GIS 10.2 using rainfall and temperature parameters obtained from 6 meteorological stations namely (Lwiro, Uvira, Bukavu, Shabunda, Itombwe, Lemera).

All layers were reclassified using four factor rating classes namely “1” as highly suitable (code: S1), “0.75” as moderately suitable (code: S2), “0.50” as marginally suitable (code: S3), and “0.2” as unsuitable for all variables in this analysis (Table 2) (FAO, 1976). The diagnostic parameters were aggregated into land quality including temperature, water availability, nutrient availability (NA), nutrient retention capacity (NRC) and erosion hazard (Table 2). The different land qualities were aggregated in ArcGIS 10.2 to infer land suitability assuming equal weight for each of them.

Table 2: Parameters used for rice suitability analysis

Parameters	**Diagnostic factor**	**Unit**	**S1** **1**	**S2** **0.75**	**S3** **0.5**	**N** **0.2**	**References**
1.Temperature	Mean temperature	°C	22-30	20-21 31-33	18-19 34-35	<15 >35	Kihoro *et al.*, 2013
2.Water availability	Rainfall	mm	1300-1600 >1600	1000-1300	700-1000	<700	Masoud *et al.*, 2013
3.Erosion hazard	Slope Texture	%	0–2 Clay, clay loam	2–4 Silty clay, silt, loam	4–6 Silt loam, sandy loam	>6 Sand	Dengiz, 2013 Kihoro *et al.*, 2013
4.Nutrient availability (NA)	pH N P K Organic carbon	- % ppm ppm %	5.5–7.3 >0.2 >25 >60 >2.0	7.4–7.8 5.1–5.5 0.1–0.2 10–25 30–60 0.8-2	7.9–8.4 4.0–5.0 <0.1 <10 <30 <0.8	>8.4 <4.0 - - - -	Dengiz, 2013 Dengiz, 2013 Dengiz, 2013 Dengiz, 2013 Halder, 2013
5. Nutrient retention capacity (NRC)	CEC	Meq /100g	25-40 >40	15-25	5-15	<5	Masoud *et al.*2013

3.2.2 Projected impact of climate change on paddy rice yield in the selected areas

3.2.2.1 Determination of historical trends in climatic parameters of Kavumu and Luberizi

Daily temperature and rainfall data covering the 1980-2010 periods were used in the determination of trends in climate parameters of Kavumu and Luberizi. This data for both sites was obtained from the NASA's Modern Era-Retrospective Analysis for Research and Applications (AgMERRA). It was grouped into monthly, seasonal and annual values. Temporal trends were determined using regression techniques. In addition, variability trend in rainfall was detected by analyzing the annual coefficient of variation data.

3.2.2.2 Characterization of projected climate in Kavumu and luberizi

Projections of rainfall and temperature values were done using the 1980-2010 as reference period (baseline period). Two projection periods were considered: Mid-century (2040-2069) and End-century (2070-2099) and two Representative Concentration Pathways (4.5 and 8.5). Twenty global circulation models (GCMs) were used in this study. The projection followed the protocol developed under the AgMIP project. Details on the model center, the institute identity and the model name of the 20 GCMs are provided in table 3.

Table 3: Identification of the 20 GCMs

Modeling Center (or Group)	Institute ID	Model Name
Beijing Climate Center ,China Meteorological	Administration BCC BCC-CSM1.1	BCC-CSM1.1(m)
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM MIROC-ESM-CHEM
College of Global Change and Earth System Science, Beijing Normal University	GCESS	BNU ESM
University of Miami - RSMAS	RSMAS	CCSM4(RSMAS)
National Center for Atmospheric Research	NCAR	CCSM4
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0, ACCESS1.3
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	Realizations by INPE	HadCM3, HadGEM2-CC, HadGEM2-ES, HadGEM2-A
Norwegian Climate Centre	NCC	NorESM1-M, NorESM1-ME
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM/CERFACS	CNRM-CM5, CNRM-CM5-2
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR
Community Earth System Model Contributors	NSF-DOENCAR	CESM1(BGC), CESM1(CAM5) CESM1(CAM5.1,FV2), CESM1(FASTCHEM) CESM1(WACCM)
National Center for Atmospheric Research	NCAR	CCSM4
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM2.1, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GFDL-HIRAM-C180, GFDL-HIRAM-C360
Canadian Centre for Climate Modeling and Analysis	CCCMA	CanESM2, CanCM4, CanAM4
Institute for Numerical Mathematics	INM	INM CM4

In addition to the individual model mean computation, assemble mean of the twenty models were computed. The change in rainfall and temperature was determined by the difference between the average projected and baseline rainfall, maximum and minimum temperatures. For impact applications, expressing the change in rainfall in percentage is more relevant than in absolute amounts. Considering that, formulas used to estimate the relative change in rainfall and temperature are given below:

$$\Delta \quad = \quad -$$

$$= \frac{(\quad - \quad) \times 100}{}$$

Where: ΔT is the change in temperature, Tp is the average projected temperature, Tb is the average baseline temperature, R is the percentage change in rainfall, Rp is the average projected rainfall, Rb is the average baseline rainfall.

3.2.2.3 Impact of historical and future climate on paddy rice yield

a. Simulation of baseline conditions

The APSIM-rice model version 7.4 was used to simulate crop yield as a function of climate conditions. The first step in the simulation process was to create the meteorological (met) files containing the required daily values for rainfall, minimum and maximum temperatures and solar radiation. The annual average ambient temperature (TAV) and the annual amplitude in monthly temperature (AMP) were calculated using long-term daily minimum and maximum temperatures. The calculated values of TAV and AMP were inserted in the met files by the software program named "tav_amp". The raw data in the met file was arranged according to used latitude (^{o}C), years, days, rainfall (mm), minimum and maximum temperature (^{o}C), solar radiation (MJ m^{-2}), TAV and AMP.

Input data related to soil characteristics include soil texture, number of layers in soil profile, soil layer depth, pH of soil for each depth, clay, silt and sand contents, organic carbon, electrical conductivity, cation exchange capacity, Aluminium (Al), Manganese (Mn), Potassium (K), Calcium, Magnesium (Mg), Sodium (Na) and Boron. Required data on soil characteristics were obtained from secondary data of soil analysis produced by the Catholic University of Bukavu soil laboratory, in the 2 selected sites. The gaps were filled by the available soil data in SOTER database.

The manager module in APSIM was used to describe the management configurations before simulation took place. The different management practices used to simulate rice yield are summarized in Table 4. A local cultivar was used to simulate rice yields for the entire 30-year period spanning 1980 to 2010. The cultivar used has been given the characteristics of a local variety (V046) used in the two catchments of interest namely Kavumu and Luberizi. Similar specifications, in terms of plant duration in seed-bed, sowing criteria were used. Management practices used to simulate rice yields are listed in table 4.

Table 4: Management practices used to simulate rice yields

Parameters	Input data
Planting method	Transplanting
Planting date	30-August to 15-september
Plant population density (plants ha-1)	160000
Transplant age	21
Plant per Hill	4
Irrigation technology	Automatic irrigation

Source: Xavier (2010).

b. Model calibration

The model was calibrated using measured grain yield data collected in the rice producing areas in Kavumu catchment from 2001 to 2008 (Xavier, 2010). Figure 7 shows the comparison of measured and predicted rice grain yield grown in Kavumu. The trend of grain yield is successfully predicted by the model. Measured grain yield ranged from 4195.45 Kgha^{-1} to 4607.65 Kgha^{-1} whereas simulated grain yield ranged from 4094.1 Kgha^{-1} to 4837.6 Kgha^{-1}. The regression is highly significant ($p<0.05$), r^2= 0.6347.

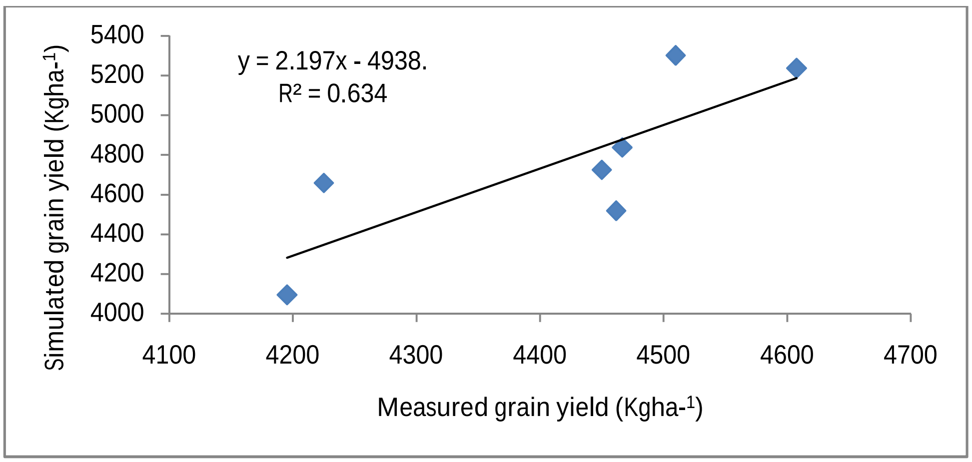


Figure 7: Comparison of measured and predicted rice grain yield grown in Kavumu catchment for years 2001-2008

C. Sensitivity analysis to climatic parameters

As mentioned above, the climatic parameters used in the model were maximum temperature (Tmax), minimum temperature (Tmin), solar radiation (Srad) and precipitation (Rain). In order to assess relative importance of these parameters on predicted rice yield, sensitivity analysis was carried out by changing one parameter at a time from the baseline scenario which reflects the actual historical conditions for the experimental site. Maximum and minimum temperatures were simultaneously increased by 1°C increments up to a total of 5°C. Rainfall was increased by 5% up to 15%. Atmospheric CO_2 concentration was kept fixed at 350 ppm and any change in solar radiation was considered. The “climate control” module was used to set incremental changes in temperature and rainfall.

Simulations were carried out by incorporating appropriate changes to “operations” file based on the conditions defined in AgMIP protocols. Tables 5 and 6 show the results of the sensitivity test in Kavumu and Luberizi. In Kavumu, temperature had a positive impact on yield. Progressive increment in maximum and minimum temperatures resulted in progressive increment in the yield. Yield increased by about 5.96%, 13.59%, 45.88%, 62.14%, and 64.74% for gradual increases in temperature of 1°C, 2°C, 3°C, 4°C and 5°C, respectively. A similar trend has been observed on biomass up to 3°C temperature increase after which biomass started declining for every increment in temperature. In Luberizi, temperature increase had a negative effect on biomass reducing it up to 9.03% when temperature was increased by 5°C. Low increments have been noticed, however, on yield with a maximum of 1.42% for an increase in temperature of 3°C. Increments in rainfall had negative effects on biomass and yield at both sites. In Kavumu, both biomass and yield decreased respectively up to 0.11% and 0.37% for 15% increment in rainfall. A similar trend has been noticed in Luberizi where biomass and yield declined respectively up to 1.92% and 2.24% for 15% increment in rainfall.

Table 5: Sensitivity of rice yield to maximum and minimum temperature in Kavumu and Luberizi catchments

Site	Tmax	Tmin	Biomass (Kg/ha)	Biomass change (%)	Yield (Kg/ha)	Yield change (%)
Kavumu	Base	Base	18505.06		4723.56	
	Base+1°C	Base+1°C	20144.52	8.86	5005.32	5.96
	Base+2°C	Base+2°C	20894.05	12.91	5365.41	13.59
	Base+3°C	Base+3°C	19335.05	4.49	6890.87	45.88
	Base+4°C	Base+4°C	18143.18	-1.96	7658.78	62.14
	Base+5°C	Base+5°C	17517.07	-5.34	7781.68	64.74
Luberizi	Base	Base	11640.57		4808.63	
	Base+1°C	Base+1°C	11415.90	-1.93	4864.56	1.16
	Base+2°C	Base+2°C	11145.11	-4.26	4868.66	1.25
	Base+3°C	Base+3°C	10927.80	-6.12	4877.15	1.42
	Base+4°C	Base+4°C	10733.23	-7.79	4861.25	1.09
	Base+5°C	Base+5°C	10589.37	-9.03	4847.03	0.80

Table 6: Sensitivity of rice yield to rainfall in Kavumu and Luberizi catchments

Site	Rainfall	Biomass (Kg/ha)	Biomass change (%)	Yield (Kg/ha)	Yield change (%)
Kavumu	Base	18505.06		4723.56	
	Base+5%r	18496.73	-0.05	4717.20	-0.13
	Base+10%r	18487.98	-0.09	4711.79	-0.25
	Base+15%r	18483.87	-0.11	4705.96	-0.37
Luberizi	Base	11640.57		4808.63	
	Base+5%r	11563.41	-0.66	4769.10	-0.82
	Base+10%r	11489.35	-1.30	4734.35	-1.54
	Base+15%r	11416.88	-1.92	4700.72	-2.24

d. Modeling future climate impact on paddy rice yield

To simulate the impact of future climate on yield, APSIM-rice model version 7.4 was used. Only the meteorological (met) files were changed. Climate data containing the projected daily values for rainfall, minimum and maximum temperatures and solar radiation generated following the AGMIP protocol was used. Rice yield for the projected future climate was simulated assuming that all other conditions remained the same. The impact was computed as a relative change in yield.

3.3 Data analysis

Average annual and seasonal values for rainfall and temperature, their standard deviations and coefficient of variation were computed. Trend analyses were used to determine seasonal and annual variations in climatic parameters from 1980 to 2010 in the study area. R software version 3.1 was used following the AgMIP protocol to evaluate climate predictions of the 20 GCMs considered. Regression techniques were also used to determine the possible relationships between projected climate parameters and yield.

CHAPTER FOUR: RESULTS

4.1 Assessment of the suitability of Kavumu and Luberizi catchments to rice growth under current climate

The rice suitability map of Kavumu and Luberizi catchments are presented in Figures 8 and 9. The Luberizi catchment (16036ha) was bigger than the Kavumu catchment covering 1744 ha. Both catchments were divided into three paddy rice suitability classes namely: moderately suitable, marginally suitable and unsuitable. Generally only a small portion of the two locations was found at most moderately suitable for rice growth (7.51% and 18.07% of the catchment in Kavumu and Luberizi, respectively). The marginally suitable class represented 72.88% and 36.09% of the catchment in Kavumu and Luberizi, respectively. The rest of the catchment (19.61% in Kavumu and 45.84% in Luberizi) was unsuitable for rice growth.

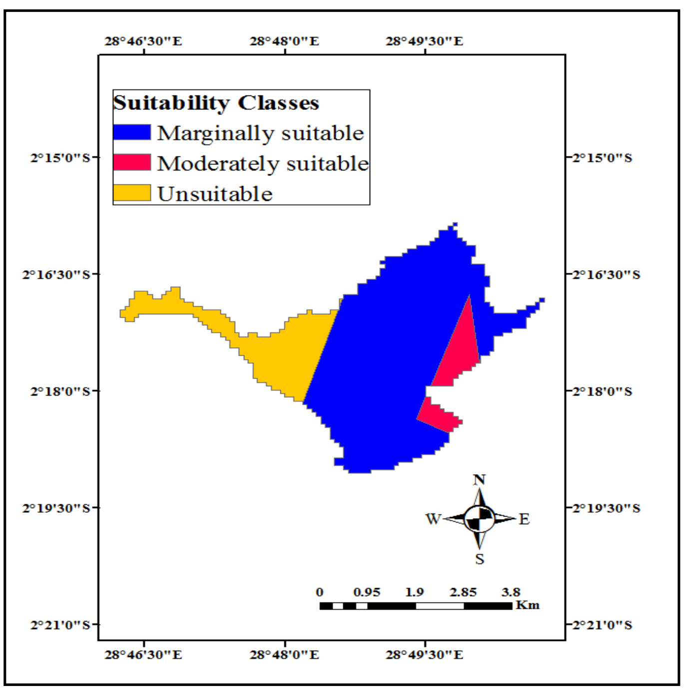


Figure 8: Rice suitability map of Kavumu catchment

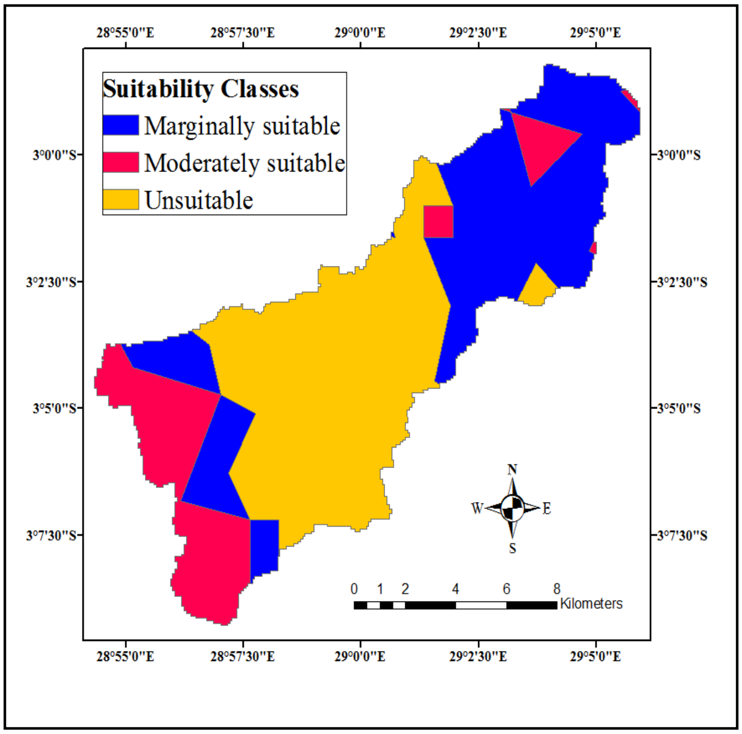


Figure 9: Rice suitability map of Luberizi catchment

4.2 Trend analysis of historical climate and its impact on paddy rice production in Kavumu and Luberizi catchments

4.2.1 Rainfall trends for the last thirty years (1980-2010) in Kavumu and Luberizi catchments

The rainfall trends for the last thirty years (1980-2010) in Kavumu and Luberizi catchments are presented in Figures 10 and 11. It can be noted that seasonal and annual rainfall amounts have been fluctuating overtime in both catchments. In Kavumu, the annual and SOND rainfall coefficient of variations (CV) showed a decreasing trend for the last thirty years (Figure 10 a and b) while MAM rainfall CVs followed a quadratic trend with a minimum (Figure 10 c). The CV of the annual and SOND rainfall declined by 0.29% annually, while that of MAM declined from 1980 to 2002 before starting to increase (Figure 10 a, b and c). In Luberizi, however, it is the annual and MAM rainfall CVs which showed a decreasing trend for the last thirty years (Figure 11 a and c) while SOND rainfall CV followed a quadratic trend with a maximum (Figure 11 b). The CV of the annual and MAM rainfall declined respectively by 0.23% and 0.05% annually, while that of MAM increased from 1980 to 2003 before starting to decrease (Figure a, b and c).

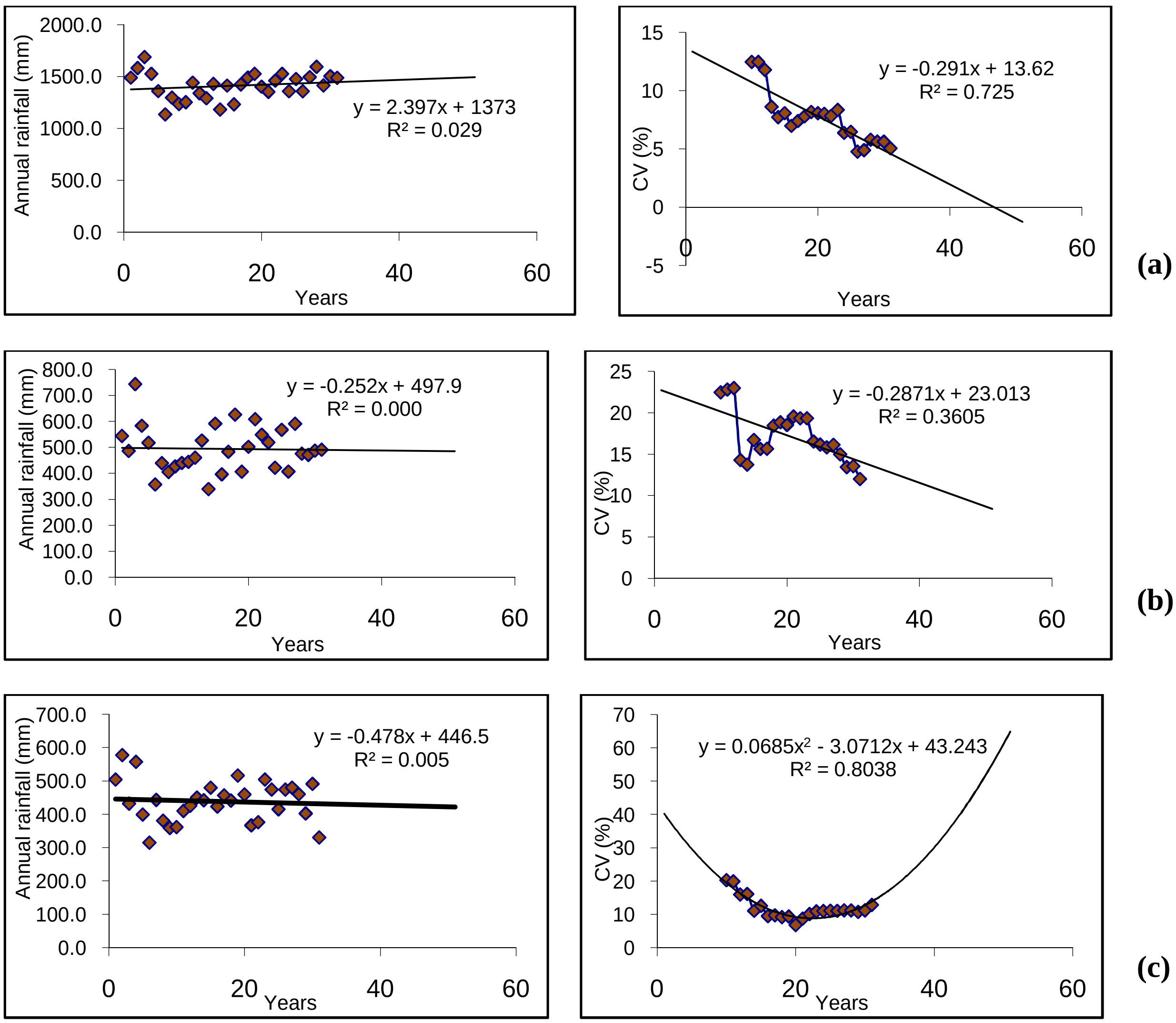


Figure 10: (a) Annual rainfall trend and its CV, (b) season 1 (SOND) rainfall trend and its CV, (c) season 2 (MAM) rainfall trend and its CV, Kavumu catchment

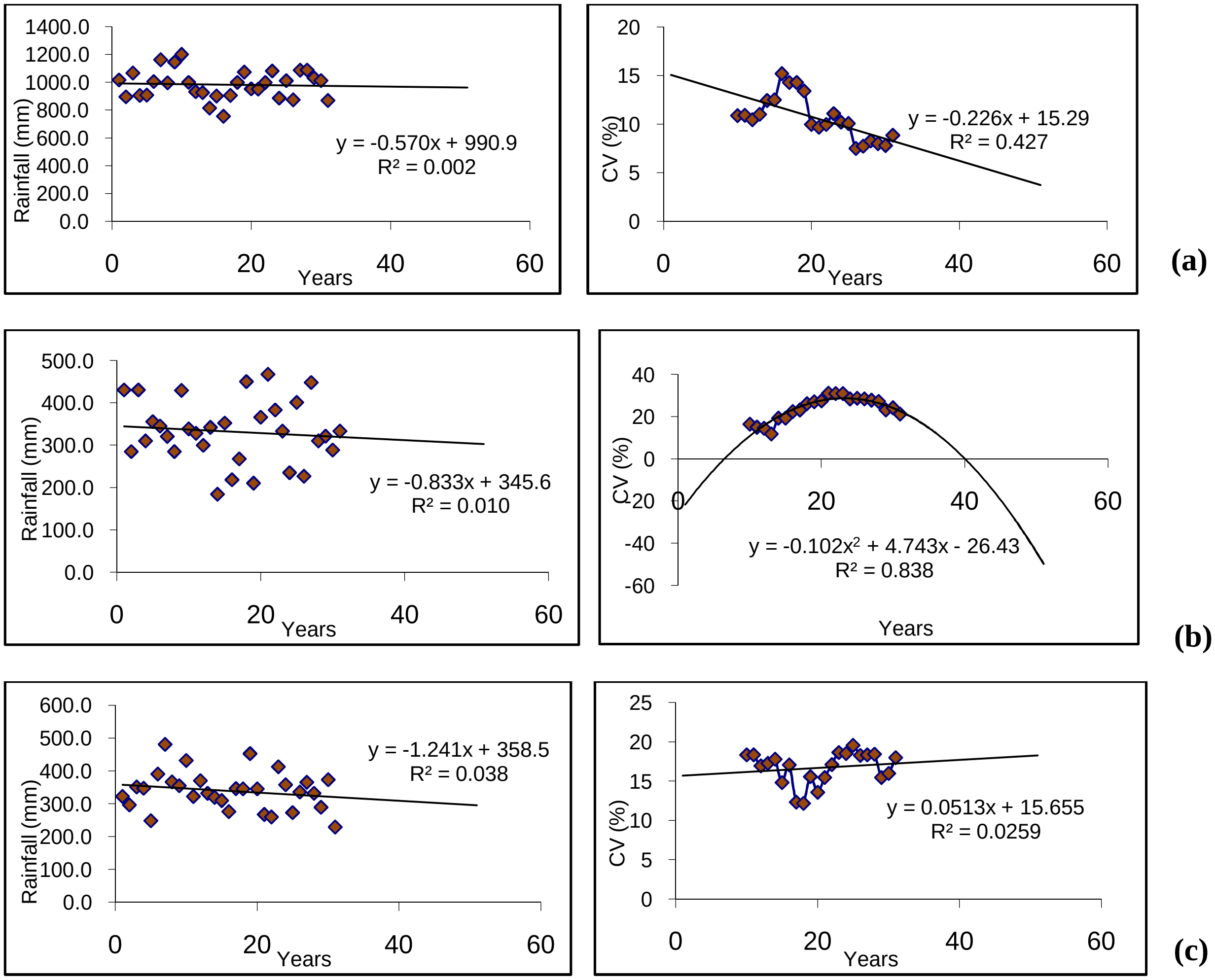
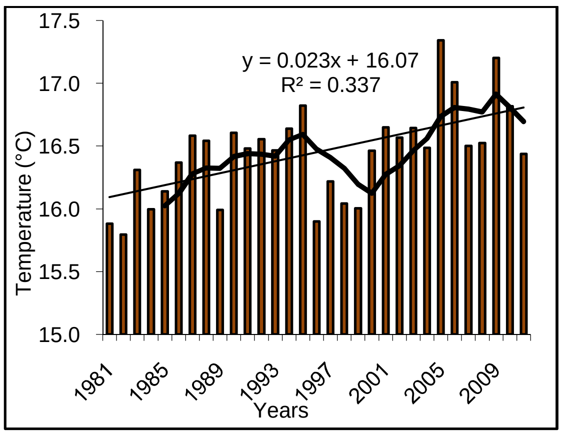


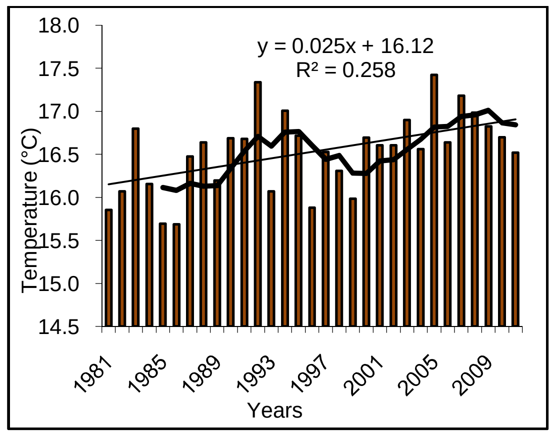
Figure 11: (a) Annual rainfall trend and its CV, (b) season 1 (SOND) rainfall trend and its CV, (c) season 2 (MAM) rainfall trend and its CV, Luberizi catchment

4.2.2 Mean temperature trend of the last thirty years (1980-2010) in Kavumu

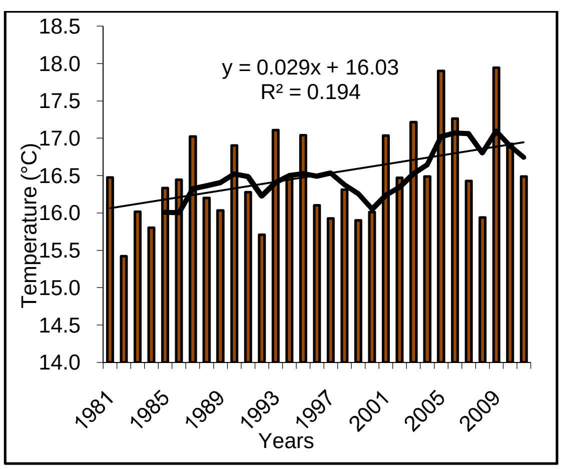
Figures 12 and 13 present mean temperature for the Kavumu and Luberizi catchments. Mean annual temperature had a significant ($p<0.001$) increasing trend over the last thirty years (1980-2010) in both catchments (Figures 12a and 13a). Similar patterns were observed for the short (Figures 12c and 13c) and long (Figures 12b and 13b) rainy periods ($p<0.01$) in both catchments.



(a)

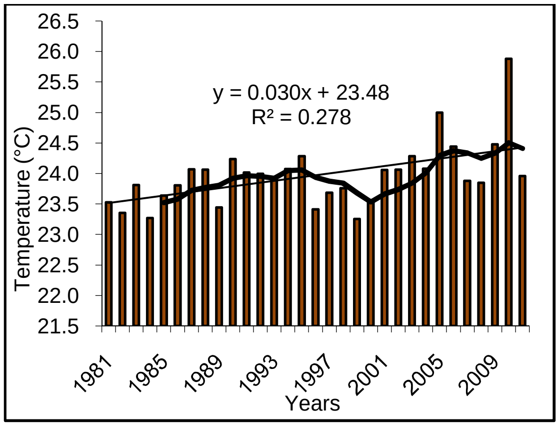


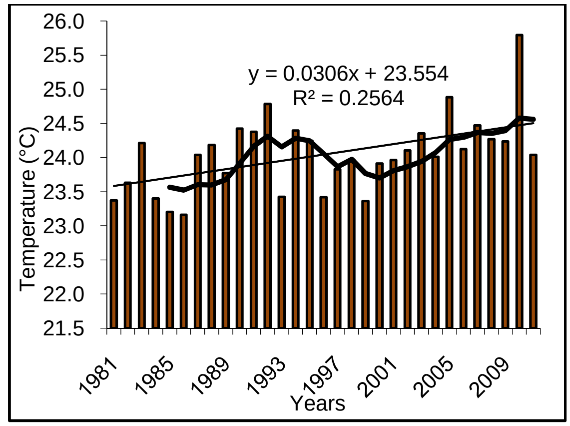
(b)



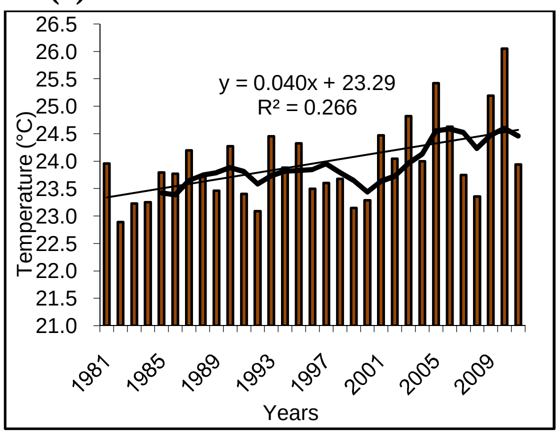
(c)

Figure 12: (a) Mean annual temperature trend, (b) mean season 1 (long rain) temperature trend, (c) mean season 2 (short rain) temperature trends, Kavumu catchment





(a) (b)



(c)

Figure 11: (a) Mean annual temperature trend, (b) mean season 1 (long rain) temperature trend, (c) mean season 2 (short rain) temperature trends, Luberizi catchment

4.2.3 Impact of historical climate on rice yield in Kavumu and Luberizi catchments

Figures 14 and 15 show rice biomass and grain yield trends from 1980 to 2010 in Kavumu and Luberizi. In both catchments biomass significantly ($p<0.001$) declined over time. Grain yield however, remained stable ($p>0.05$) in Kavumu (Figure 14) but significantly ($p<0.001$) declined in Luberizi over time (Figure 15). Biomass appeared to be more sensitive to climate variability and tended to decline faster than grain yield.

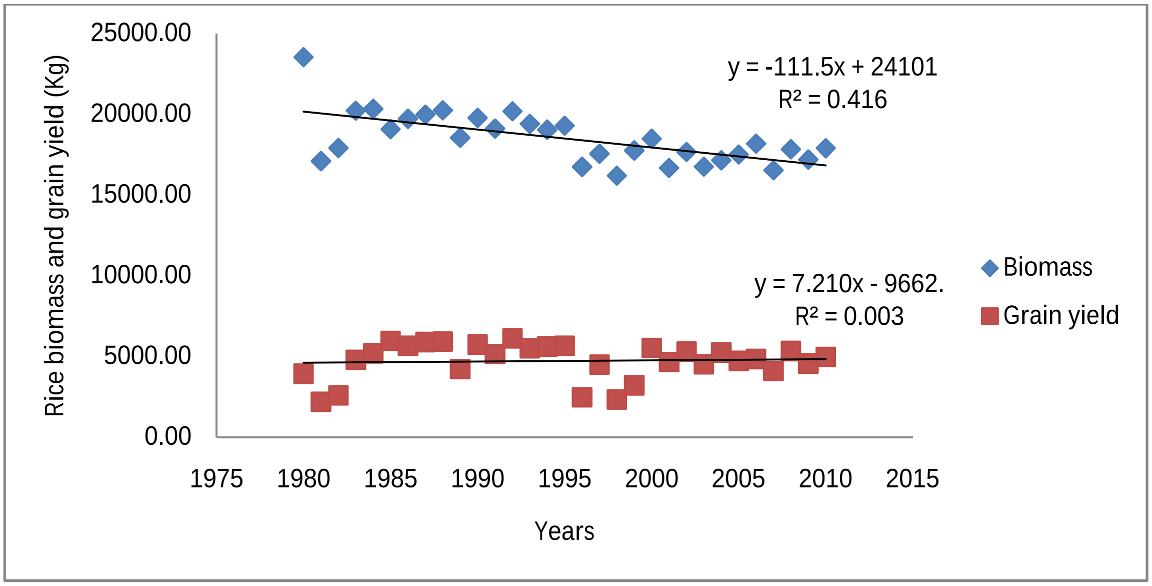


Figure 12: Rice biomass and grain yield trends from 1980 to 2010 in Kavumu catchment

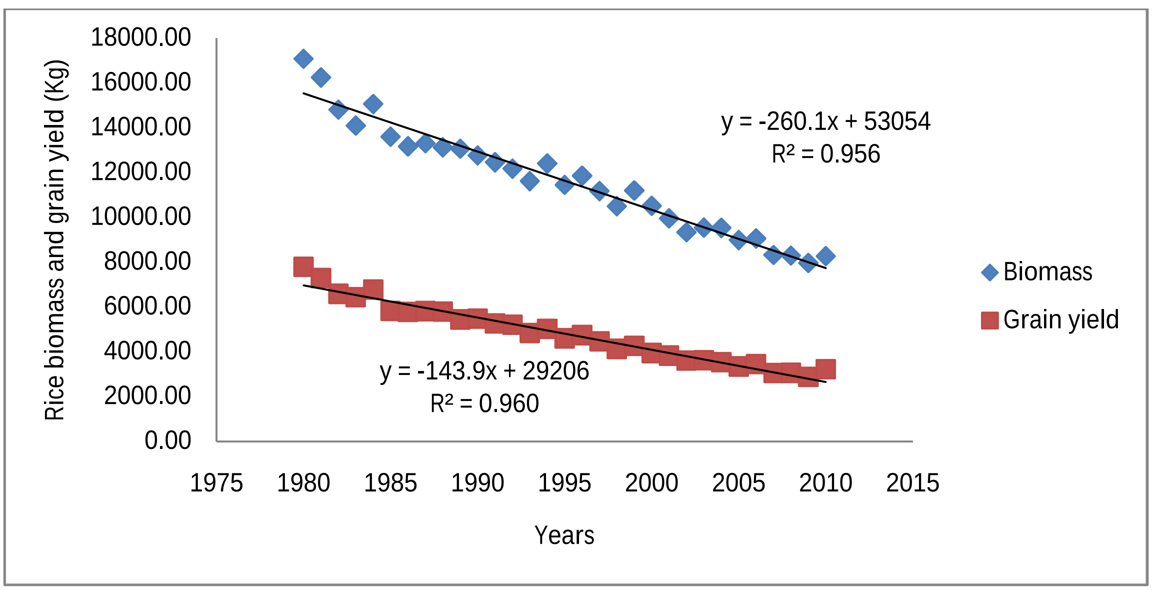


Figure 13: Rice biomass and grain yield trends from 1980 to 2010 in Luberizi catchment

4.3 Characterization of projected climate in Kavumu and Luberizi catchments

4.3.1 Projected temperature variation in Kavumu catchment under RCP 4.5 and RCP 8.5 in mid century

Projected minimum and maximum temperature variations under RCP 4.5 and RCP 8.5 in Kavumu catchment in the mid-century are presented in figures 16 and 17. The magnitude of the change varied from one model to the other. In 80% of the cases, the magnitude of positive change was greater under RCP 8.5 compared to RCP 4.5. All the models predicted an increase in minimum temperature ranging from 1.06 to 2.88°C and from 1.15 to 3.64°C under RCP 4.5 and RCP 8.5, respectively (Figure 16). The highest increase under RCP 4.5 was predicted by the HadGEM2-ES model while the lowest increase was predicted by the GFDL-ESM2G model. Under RCP 8.5 the highest increase was predicted by the inmcm4 model while the lowest increase was predicted by the GFDL-ESM2M model. For maximum temperature, under both scenarios, the majority of the models (95%) considered, predicted an increase ranging from 0.88 to 2.50°C and from 1.11 to 3.41°C under RCP 4.5 and RCP 8.5, respectively (Figure 17). Only the MIROC-ESM model under RCP 4.5 and the CCSM4 model under RCP 8.5 predicted decreases in maximum temperature of 0.68 and 0.78°C, respectively. CSIRO-Mk3-6-0 and ACCESS1-0 models predicted the highest increase while BNU-ESM and HadGEM2-CC predicted the lowest increase under RCP 4.5 and RCP 8.5, respectively.

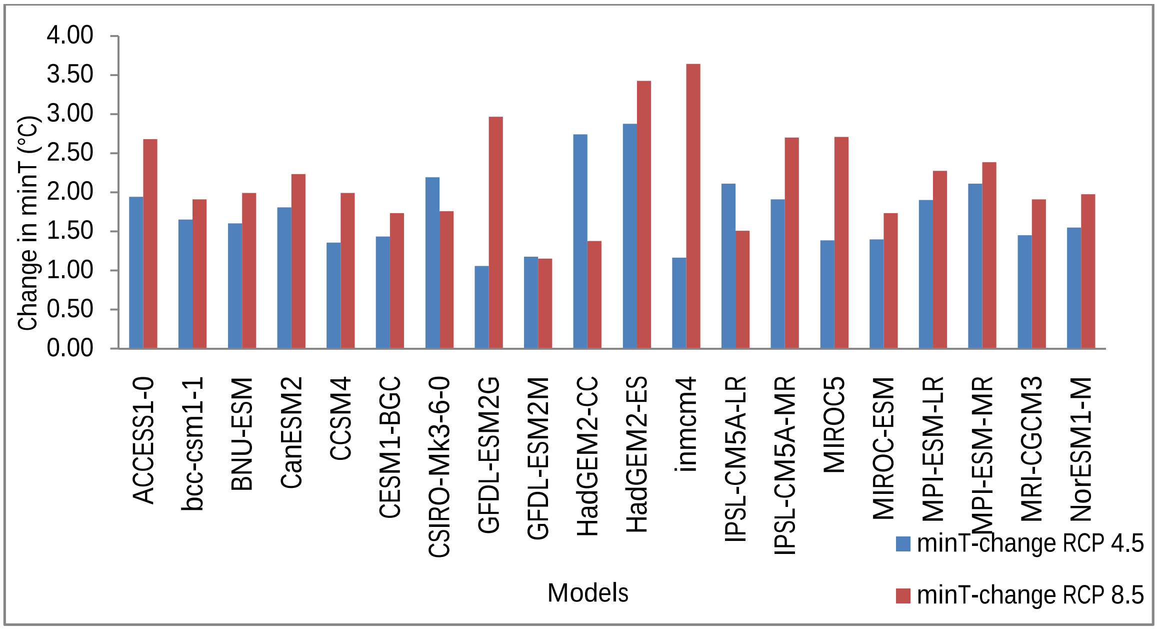


Figure 14: Projected minimum temperature variation in mid-century under RCP 4.5 and 8.5 in Kavumu catchment

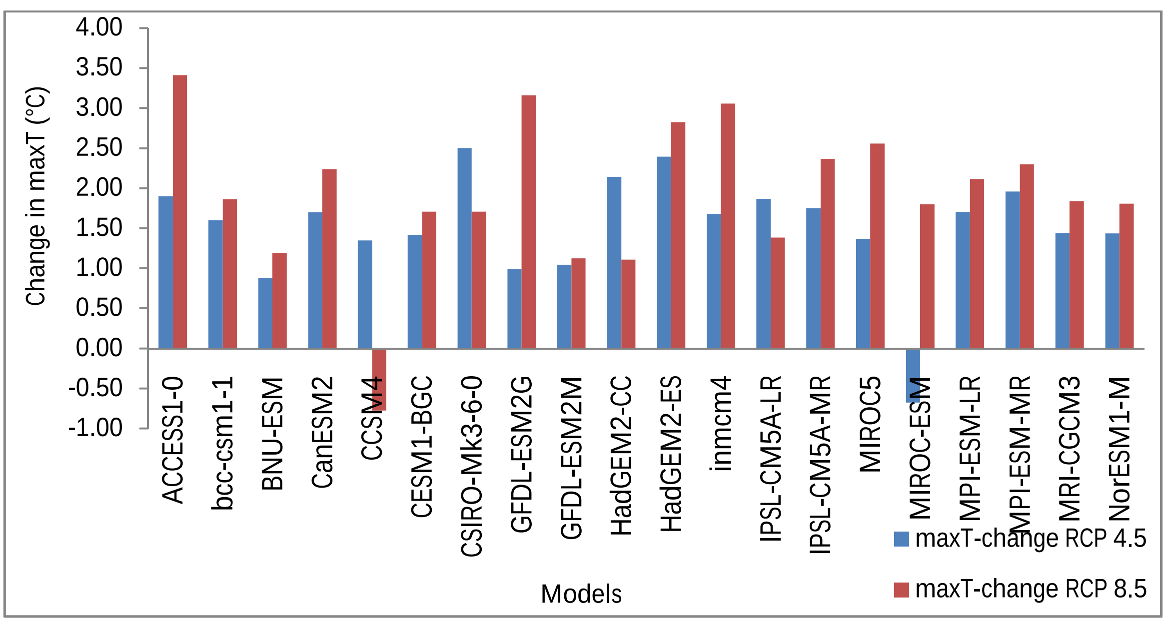


Figure 15: Projected maximum temperature variation in mid-century under RCP 4.5 and 8.5 in Kavumu catchment

4.3.2 Projected temperature variation in Kavumu catchment under RCP 4.5 and RCP 8.5 in end-century

Figures 18 and 19 illustrate the projected minimum and maximum temperature variation under RCP 4.5 and RCP 8.5 in Kavumu catchment in the end-century. The magnitude of the change also varied from model to model. In all cases, the magnitude of positive change was greater under RCP 8.5 in comparison with RCP 4.5. All the models predicted an increase in minimum temperature ranging from 1.53 to 3.22°C and from 2.75 to 5.50°C under RCP 4.5 and RCP 8.5, respectively (Figure 18). The highest increase under RCP 4.5 was predicted by the HadGEM2-CC model while the lowest increase was predicted by the NorESM1-M model. Under RCP 8.5 the highest increase was predicted by both HadGEM2-ES and HadGEM2-CC models while the lowest increase was predicted by NorESM1-M. Similarly for maximum temperature, all the models predicted an increase ranging from 1.18 to 3.25°C and from 2.42 to 5.64°C under RCP 4.5 and RCP 8.5, respectively (Figure 19). The highest increase under RCP 4.5 was predicted by the HadGEM2-CC model while the lowest increase was predicted by the IPSL-CM5A-LR model. Under RCP 8.5 the highest increase was predicted by the HadGEM2-ES model while the lowest increase was predicted by BNU-ESM.

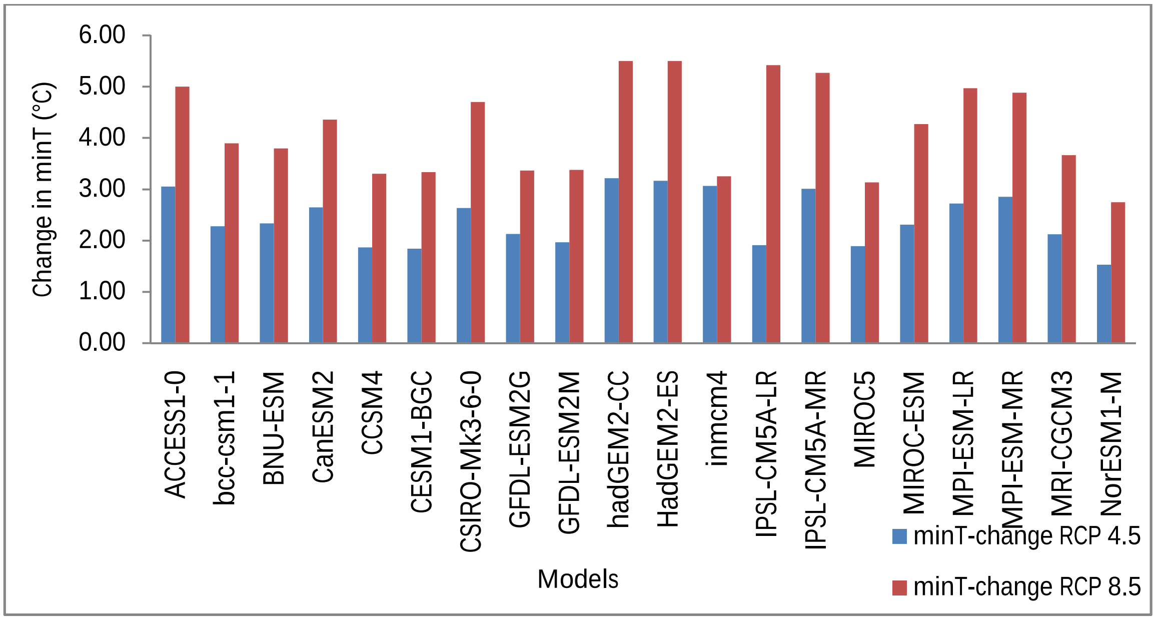


Figure 16: Projected minimum temperature variation end-century under RCP 4.5 and 8.5 in Kavumu catchment

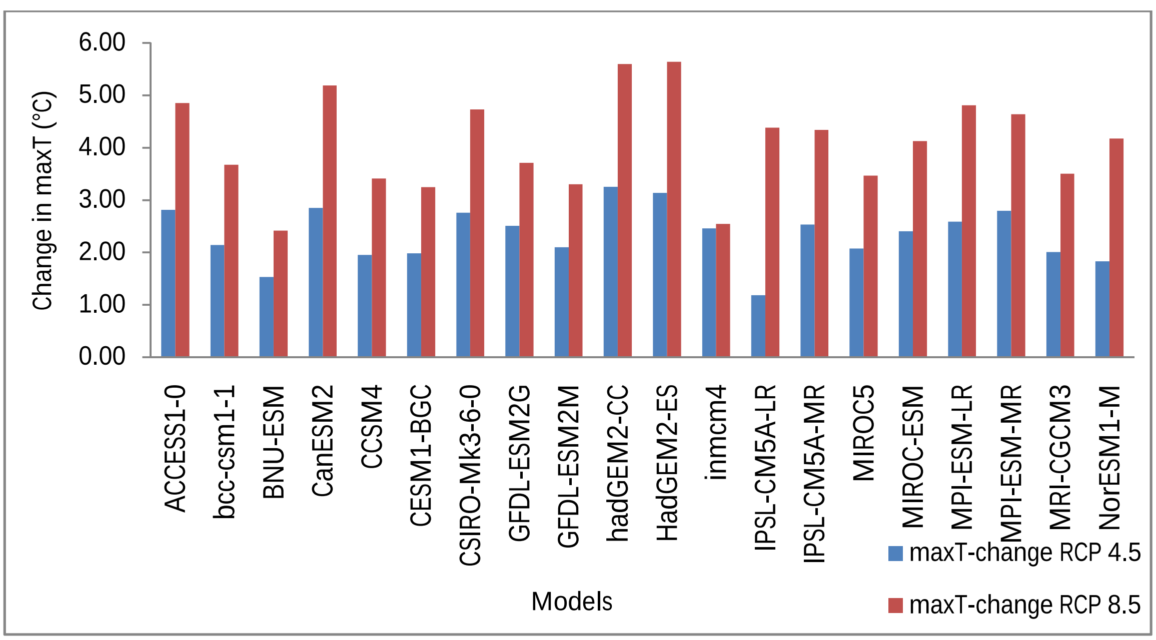


Figure 17: Projected maximum temperature variation end-century under RCP 4.5 and 8.5 in Kavumu catchment

4.3.3 Projected rainfall change in Kavumu catchment under RCP 4.5 and RCP 8.5 in mid and end-century

Figures 20 and 21 show the projected rainfall change under RCP 4.5 and RCP 8.5 in Kavumu catchment in the mid and end-century. As for temperature, the magnitude of projected rainfall change varied from one model to another. In 60% of cases in mid-century and 80% of cases in end-century, the magnitude of positive change was greater under RCP 8.5 with respect to RCP 4.5 (Figure 20). The majority (75%) of the models predicted an increase in rainfall ranging from 0.63 to 21.38 % while 25% predicted a decrease ranging from 3.52 to 9.99% in mid-century, under RCP 4.5. For RCP 8.5, 70% of the models predicted an increase in rainfall ranging from 0.40 to 29.04% while 30% predicted a decrease ranging from 0.81 to 8.34%. The highest increase was predicted by the IPSL-CM5A-LR model while the highest decline was predicted by the MIROC-ESM model under RCP 4.5. For RCP 8.5, the highest increase was predicted by the MIROC5 model while the highest decline was predicted by the GFDL-ESM2G model. Regarding end-century, under RCP 4.5, the majority (75%) of the models predicted an increase in rainfall ranging from 0.29 to 26.82 % while 25% predicted a decrease ranging from 1.95 to 7.69% (Figure 21). For RCP 8.5, 90% of the models predicted an increase in rainfall ranging from 0.53 to 55.49% while two models, CSIRO-Mk3-6-0 and HadGEM2-ES predicted decreases of 1.89 and 4.13%, respectively. The highest increase was predicted by inmcm4 model while the highest decline was predicted by the GFDL-ESM2G model under RCP 4.5. For RCP 8.5, the highest increase has been predicted by the IPSL-CM5A-MR model while the highest decline was predicted by the HadGEM2-ES model.

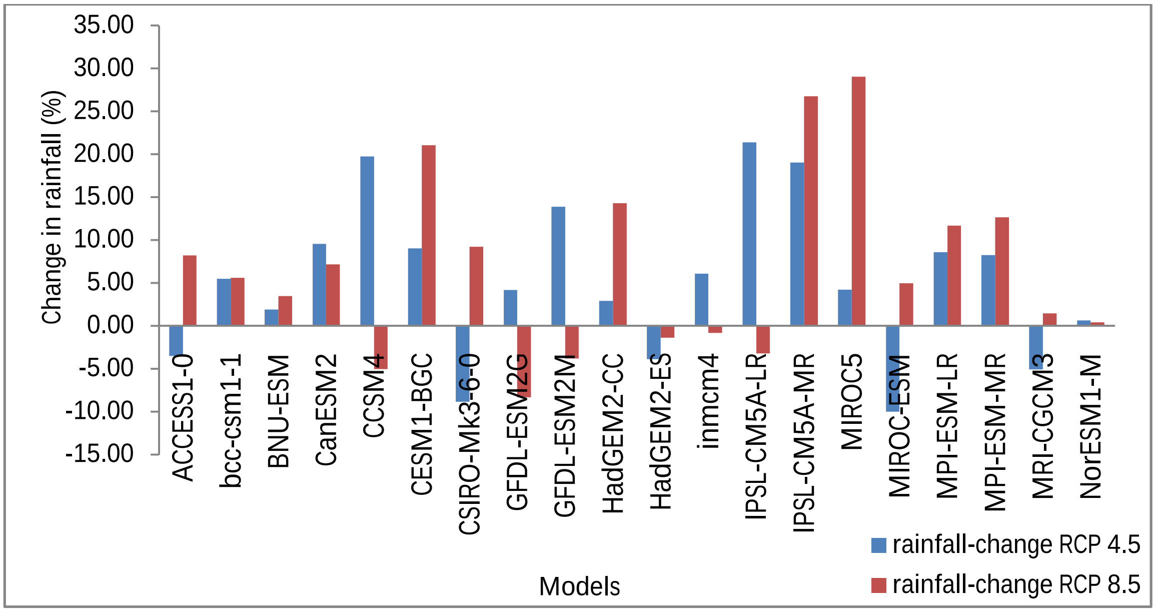


Figure 18: Projected rainfall change mid-century under RCP 4.5 and RCP 8.5 in Kavumu catchment

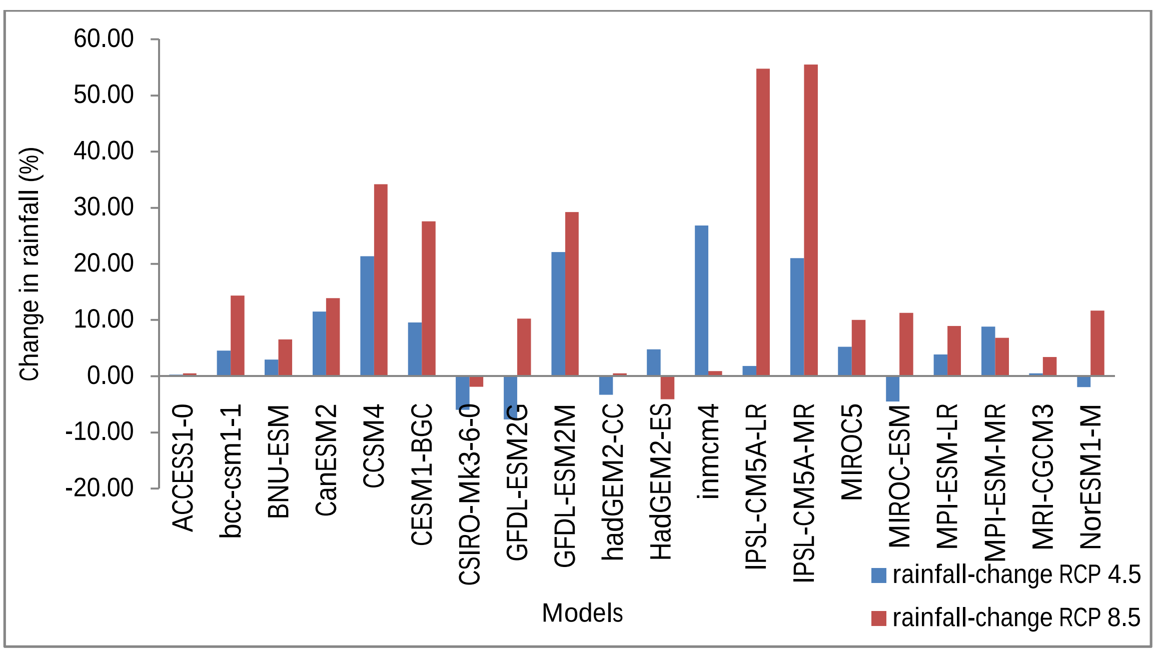


Figure 19: Projected rainfall change end-century under RCP 4.5 and RCP 8.5 in Kavumu catchment

The assembled means of the projected changes in temperature and rainfall in Kavumu catchment are presented in table 7. Projected rainfall and temperature for mid and end-centuries are likely to increase for the different RCPs and periods. The increment in rainfall and minimum and maximum temperatures will be higher in the end-century compared to the mid-century and for the 8.5 RCP scenario compared to the 4.5 RCP scenario. The increment in minimum temperature will be slightly greater than the increment in maximum temperature.

Table 7: Assembled means of projected changes in climate in mid and end centuries under RCP 4.5 and RCP 8.5 in Kavumu catchment

Period	RCP 4.5			RCP 8.5		
	ΔTmax	ΔTmin	Rainfall	ΔTmax	ΔTmin	Rainfall
	°C		%	°C		%
Mid-century	1.52	1.74	5.18	1.94	2.20	6.67
End-century	2.35	2.43	6.10	4.09	4.19	14.72

4.3.4 Projected temperature variation in Luberizi catchment under RCP 4.5 and RCP 8.5 in mid century

The projected minimum and maximum temperature variations under RCP 4.5 and RCP 8.5 in mid-century for Luberizi catchment are shown in Figures 22 and 23. The magnitude of the change varied between models. In all cases in mid-century and in 90% of cases in end-century, the magnitude of positive change was greater under RCP 8.5 compared to RCP 4.5. All the models predicted an increase in minimum temperature ranging from 0.91 to 4.48°C and from 1.12 to 5.20°C under RCP 4.5 and RCP 8.5, respectively. The highest increase under both scenarios was predicted by the ACCESS1-0 model while the lowest increase was predicted by the inmcm4 model (Figure 22).

Similarly for maximum temperature, all the models predicted an increase ranging from 0.83 to 3.29°C and from 1.11 to 4.09°C under RCP 4.5 and RCP 8.5, respectively (Figure 23). The highest increase under both scenarios was predicted by the ACCESS1-0 model while the lowest increase was predicted by inmcm4 model and GFDL-ESM2M under RCP 4.5 and RCP 8.5, respectively.

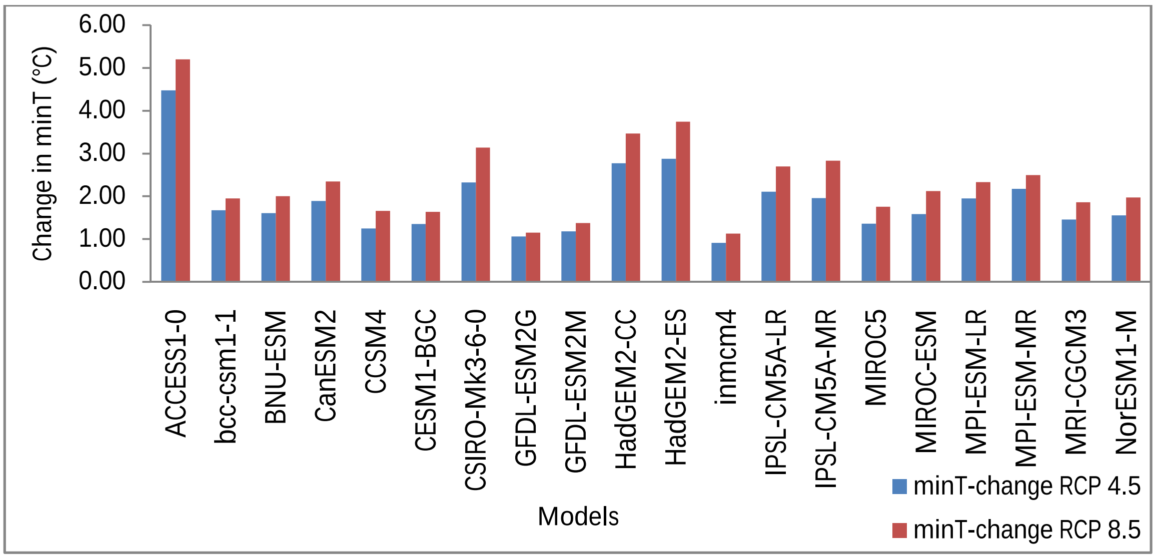


Figure 20: Projected minimum temperature variation mid-century under RCP 4.5 and RCP 8.5 in Luberizi catchment

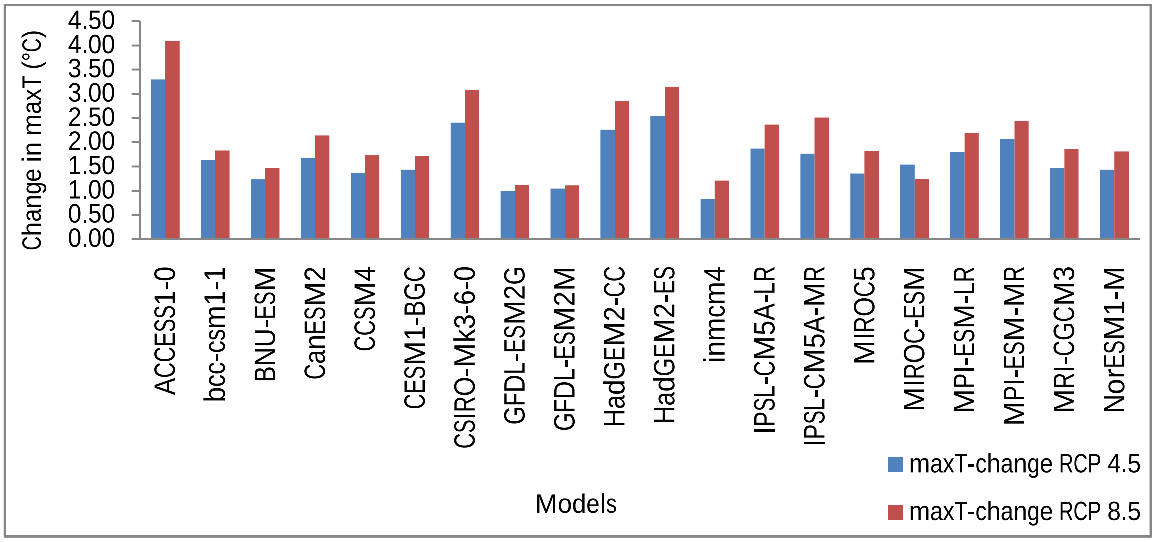


Figure 21: Projected maximum temperature variation mid-century under RCP 4.5 and RCP 8.5 in Luberizi catchment

4.3.5 Projected temperature variation in Luberizi catchment under RCP 4.5 and RCP 8.5 in end-century

The projected minimum and maximum temperature variations under RCP 4.5 and RCP 8.5 in end-century for Luberizi catchment are presented in Figures 24 and 25. The magnitude of the change varied from model to model. In all cases, the magnitude of positive change was greater under RCP 8.5 with respect to RCP 4.5. All the models predicted an increase in minimum temperature ranging from 1.53 to 5.41°C and from 2.78 to 7.27°C under RCP 4.5 and RCP 8.5, respectively. The highest increase under both scenarios was predicted by ACCESS1-0 model while the lowest increase was predicted by NorESM1-M and inmcm4 model under RCP 4.5 and RCP 8.5, respectively (Figure 24). Similarly for maximum temperature, under both scenarios, all the models predicted an increase ranging from 1.15 to 4.12°C and from 2.34 to 6.12°C under RCP 4.5 and

RCP 8.5, respectively (Figure 25). The highest increase under both scenarios was predicted by ACCESS1-0 model while the lowest increase was predicted by inmcm4 model.

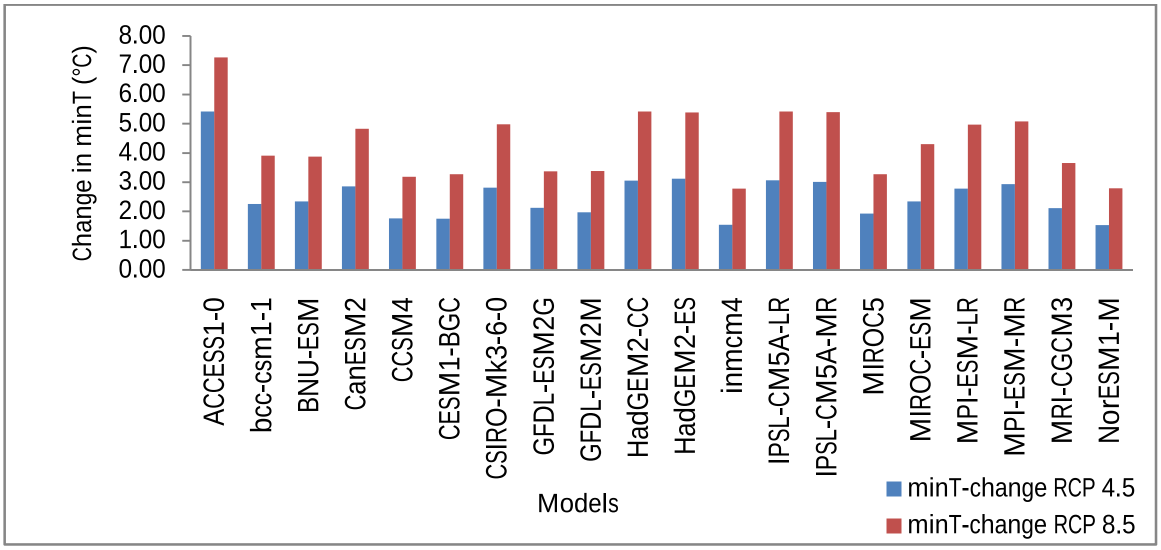


Figure 22: Projected minimum temperature variation end-century under RCP 4.5 and RCP 8.5 in Luberizi catchment

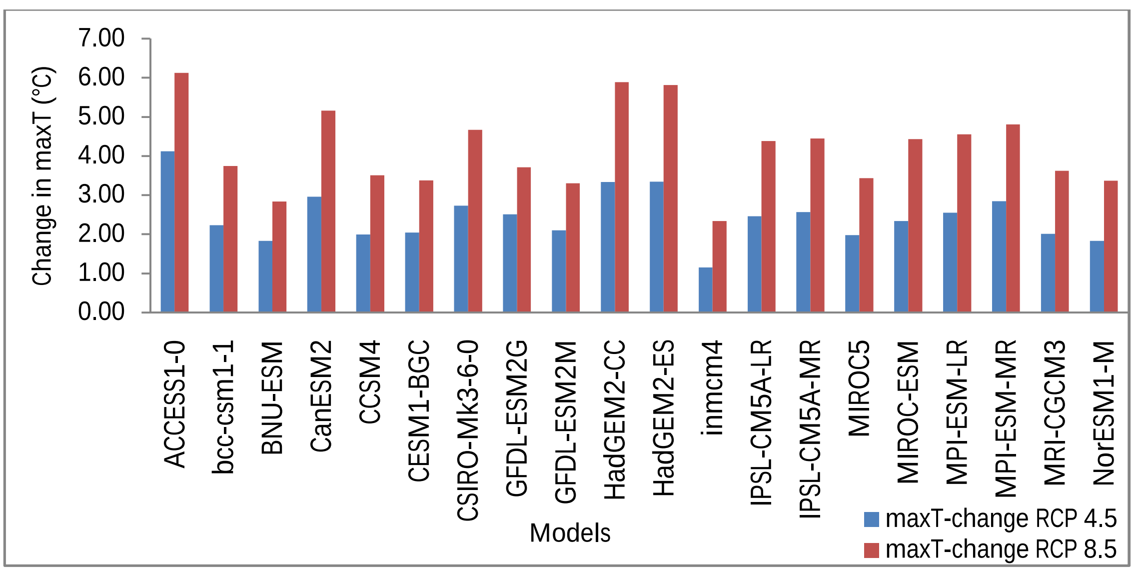


Figure 23: Projected maximum temperature variation end-century under RCP 4.5 and RCP 8.5 in Luberizi catchment

4.3.6 Projected rainfall change in Luberizi catchment under RCP 4.5 and RCP 8.5 in mid and end-century

Figures 26 and 27 show the projected rainfall changes under RCP 4.5 and RCP 8.5 in mid and end-centuries. As for temperature, the magnitude of projected rainfall change varied from one model to another. In most cases, the magnitude of positive change was greater under RCP 8.5 in comparison with RCP 4.5 while the one of negative change was greater under RCP 4.5 compared to RCP 8.5. The majority (70%) of the models predicted an increase in rainfall ranging from 0.40 to 21.26 % while 30% predicted a decrease ranging from 1.87% to 14.40% in mid-century, under RCP 4.5. For RCP 8.5, 70% of the models predicted an increase in rainfall ranging from 1.36 to 26.81% while 30% predicted a decrease ranging from 0.78 to 13.45%. Under both scenarios, the highest increase was predicted by the IPSL-CM5A-LR model while the highest decline was predicted by the ACCESS1-0 model (Figure 26). In the end-century, under RCP 4.5, 65% of the models predicted an increase in rainfall ranging from 0.01 to 26.94 % while 35% predicted a decrease ranging from 0.34 to 10.62%. For RCP 8.5, 70% of the models predicted an increase in rainfall ranging from 0.13 to 53.91% while 30% predicted a decrease ranging from 0.75 to 12.27%, respectively. Under both scenarios, the highest increase was predicted by the IPSL-CM5A-LR model while the highest decline was predicted by the ACCESS1-0 model (Figure 27).

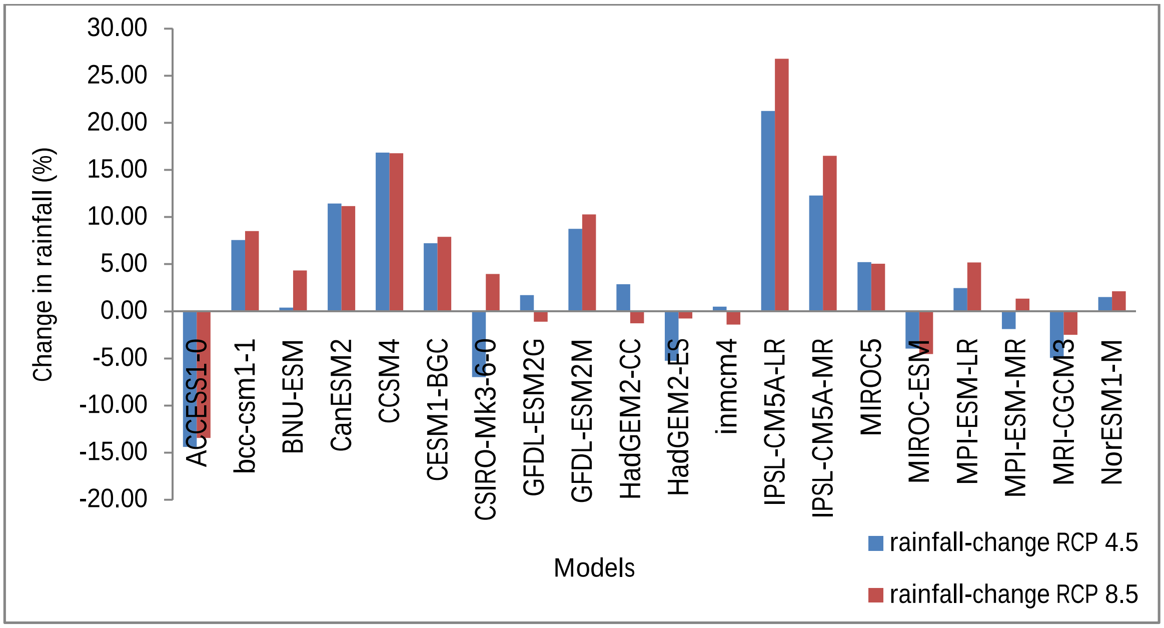


Figure 24: Projected rainfall change in mid-century under RCP 4.5 and RCP 8.5 in Luberizi catchment

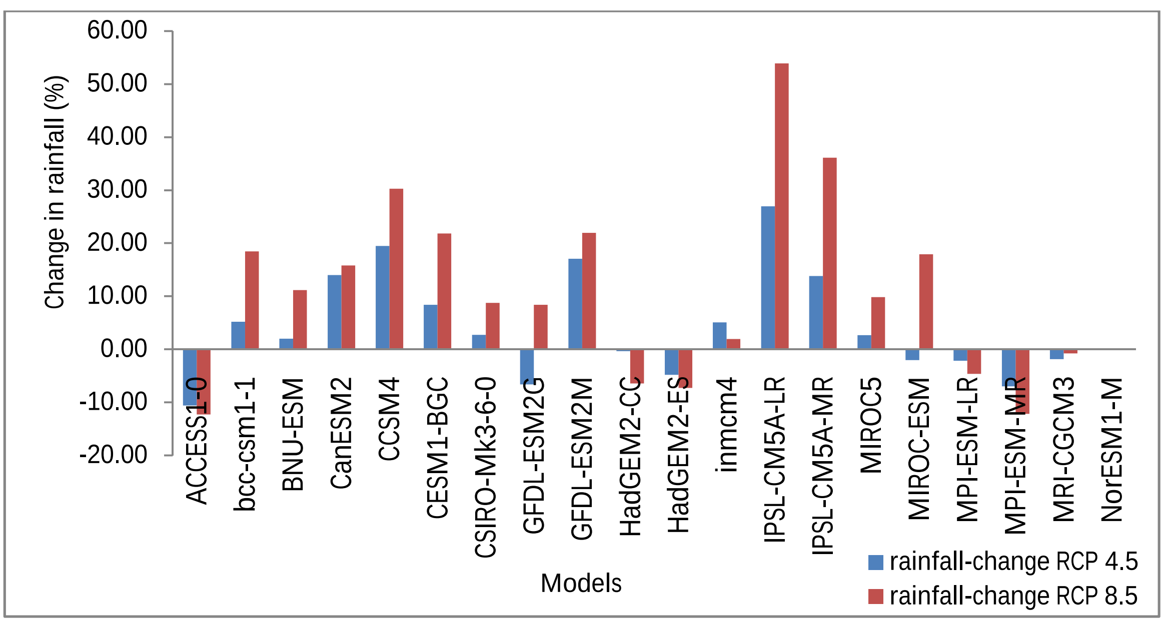


Figure 25: Projected rainfall change in end-century under RCP 4.5 and RCP 8.5 in Luberizi catchment

The assembled means of the projected changes in temperature and rainfall are presented in table 8. Just as it was for Kavumu catchment, the projected rainfall and temperature for mid and end-centuries are likely to increase for the different RCPs and periods. The increment in rainfall and minimum and maximum temperatures will also be higher in the end-century compare to mid-century and for the 8.5 RCP scenario compared to the 4.5 RCP scenario and the increment in minimum temperature will be slightly greater than the increment in maximum temperature.

Table 8: Assembled means of projected change in climate in mid and end centuries under RCP 4.5 and RCP 8.5 in Luberizi catchment

Period	RCP 4.5			RCP 8.5		
	ΔTmax	ΔTmin	Rainfall	ΔTmax	ΔTmin	Rainfall
	°C		%	°C		%
Mid-century	1.70	1.88	3.14	2.09	2.34	4.74
End-century	2.45	2.54	4.10	4.18	4.33	10.65

4.4 Impact of climate change on biomass and grain yield in Kavumu and Luberizi

4.4.1 Impact of climate change on paddy rice biomass in Kavumu catchment under RCP 4.5 and RCP 8.5 in mid-century

The impact of climate change on paddy rice biomass in Kavumu catchment under RCP 4.5 and RCP 8.5 in mid-century is presented in Figure 28. The magnitude of the change varied from one model to the other. In 65% of cases the magnitude of positive change was greater under RCP 4.5 when compared to RCP 8.5. The majority of the models (95%) considered predicted an increase in biomass ranging from 4.05 to 17.62% under

RCP 4.5. Only the MIROC-ESM model predicted a decrease in biomass of 2.02%. For RCP 8.5, the majority of the models (90%) predicted an increase in biomass, as well, ranging from 1.50 to 16.76%. Only two models, CCSM4 and ACCESS1-0, predicted decreases in biomass of 0.87% and 18.35%, respectively. The MPI-ESM-LR model predicted the highest increase under RCP 4.5 while for RCP 8.5, CESM1-BGC predicted the highest change (17.2%) while ACCESS1-0 predicted the lowest.

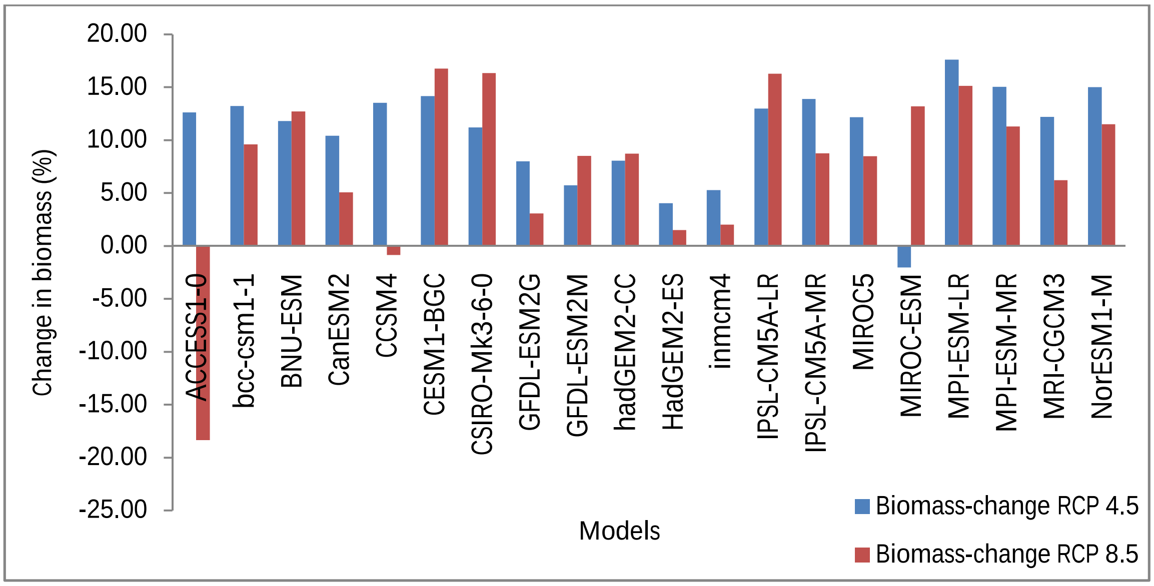


Figure 26: Impact of climate change on biomass in Kavumu catchment under RCP 4.5 and RCP 8.5 in mid-century

4.4.2 Impact of climate change on paddy rice biomass in Kavumu catchment under RCP 4.5 and RCP 8.5 in end-century

Figure 29 presents the impact of climate change on paddy rice biomass in Kavumu catchment under RCP 4.5 and RCP 8.5 in the end-century. The magnitude of the change also varied from one model to the other. Most of the models (90%) considered predicted an increase in biomass ranging from 0.63 to 17.12% under RCP 4.5. Only two models, CanESM2 and ACCESS1-0 predicted decreases in biomass of 1.36% and 2.77%, respectively. For RCP 8.5, however, the majority of the models (85%) considered predicted a decrease in biomass ranging from 0.64 to 17.58%. Only three models, CCSM4, CESM1-BGC and inmcm4 predicted increases in biomass of 0.56%, 2.74% and 6.9%, respectively. The NorESM1-M model predicted the highest increase (16.76%) under RCP 4.5 while the ACCESS1-0 model predicted the highest decline (2.77%). For RCP 8.5, inmcm4 model predicted the highest increase (6.9%) while NorESM1-M predicted the highest decline (17.58%).

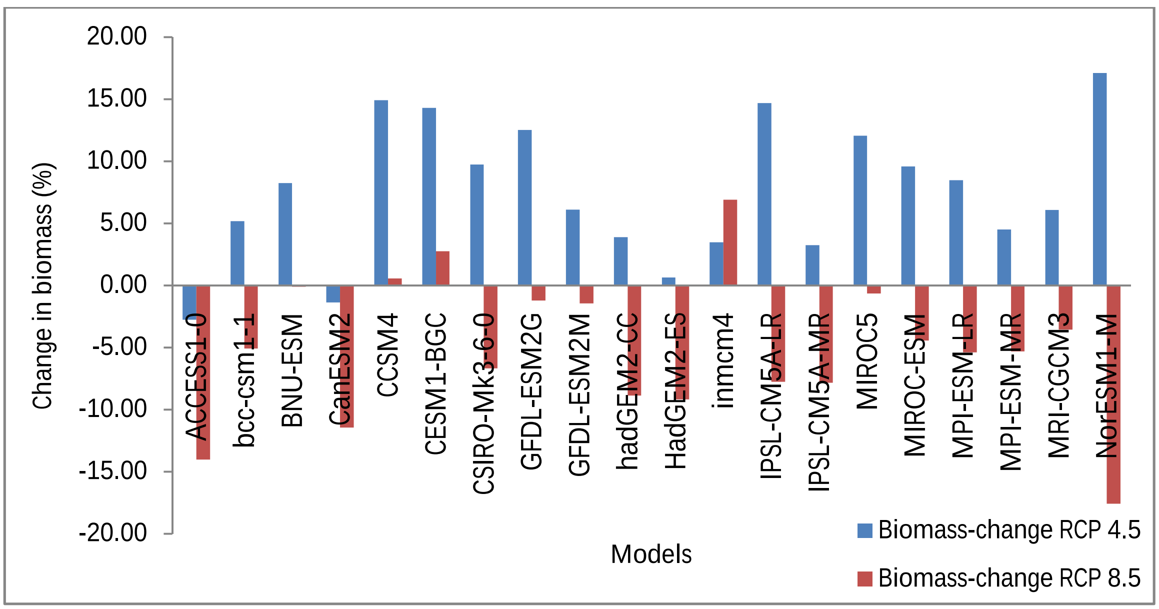


Figure 27: Impact of climate change on biomass in Kavumu catchment under RCP 4.5 and RCP 8.5 in end-century

4.4.3 Impact of climate change on paddy rice biomass in Luberizi catchment under RCP 4.5 and RCP 8.5 in mid-century

Figure 30 presents the impact of climate change on paddy rice biomass in Luberizi under RCP 4.5 and RCP 8.5 in mid-century. The magnitude of the change varied from one model to the other. In most cases (90%), the magnitude of the negative change was greater under RCP 8.5 compared to RCP 4.5. In both scenarios, all the models considered predicted a decrease in biomass. Most of the decline (95%) under RCP 4.5 ranged from 1.25 to 8.4%, with MIROC-ESM predicting the lowest. The ACCESS1-0 model predicted the highest decline of up to 29.51%. For RCP 8.5, most of the decline (95%) ranged from 1.59 to 10.57%, with GFDL-ESM2G predicting the lowest and ACCESS1-0 predicting the highest decline of up to 31.74%.

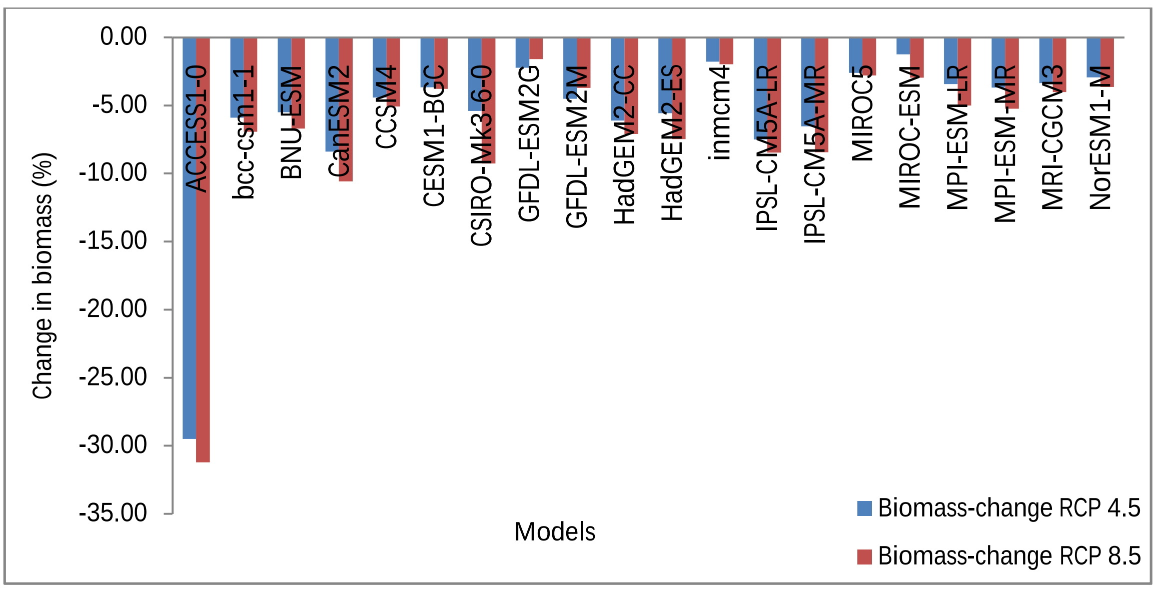


Figure 28: Impact of climate change on paddy rice biomass in Luberizi catchment under RCP 4.5 and RCP 8.5 in mid century

4.4.4 Impact of climate change on paddy rice biomass in Luberizi catchment under RCP 4.5 and RCP 8.5 in end-century

Figure 31 presents the impact of climate change on paddy rice biomass in Luberizi catchment under RCP 4.5 and RCP 8.5 in the end-century. The magnitude of the change also varied from model to model. In all cases, the magnitude of negative change was greater under RCP 8.5 in comparison with RCP 4.5.In both scenarios, all the models considered predicted a decrease in biomass. Most of the decline (95%) under RCP 4.5 ranged from 1.68 to 12.74%, with GFDL-ESM2G predicting the lowest. Also, just like in the mid-century, only the ACCESS1-0 model predicted a very high decline going up to 31.74%. For RCP 8.5, most of the decline (95%) ranged from 3.21 to 17.89%, with NorESM1-M predicting the lowest and again only the ACCESS1-0 model predicting a very high decline going up to 34.82%.

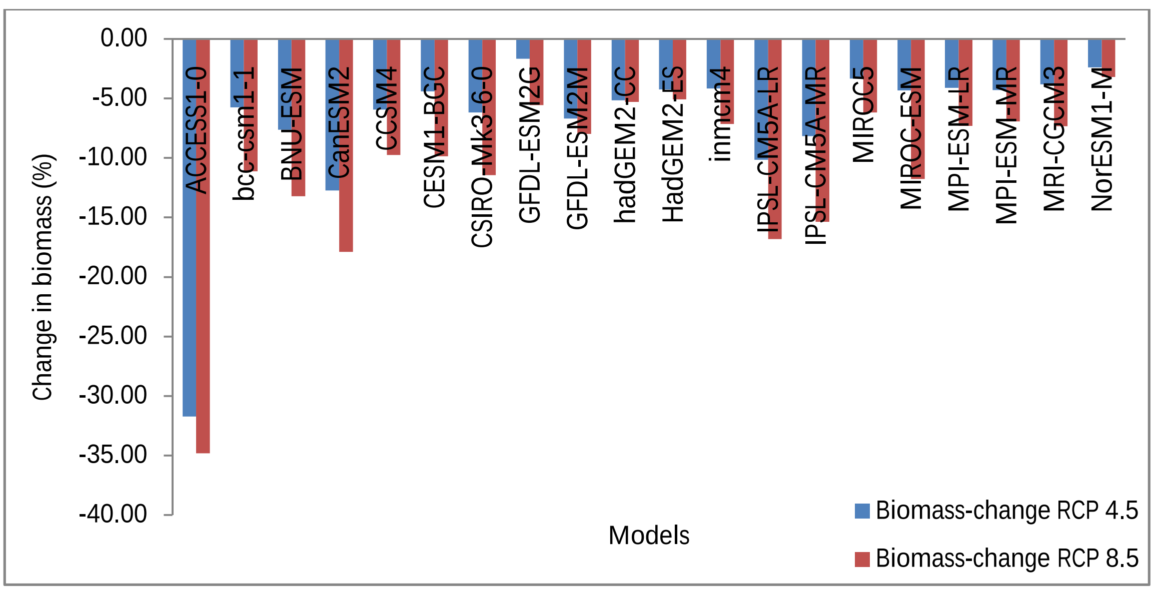


Figure 29: Impact of climate change on paddy rice biomass in Luberizi catchment under RCP 4.5 and RCP 8.5 in end-century

4.4.5 Impact of climate change on paddy rice grain yield in Kavumu catchment under RCP 4.5 and RCP 8.5 in mid-century

The impact of climate change on paddy rice grain yield in Kavumu catchment under RCP 4.5 and RCP 8.5 in the mid-century varied from model to model (Figure 32). In 70% of cases, the magnitude of positive change was greater under RCP 8.5 when compared to RCP 4.5. The majority of the models (90%) considered predicted an increase in yield under RCP 4.5 ranging from 2.69 to 44.9%. Only two models, MIROC-ESM and inmcm4 predicted decreases in yield of 2.29% and 4.27%, respectively. For RCP 8.5, all the models considered predicted an increase in grain yield ranging from 0.28 to 55.13%. The highest increases were predicted by the HadGEM2-ES model under both scenarios while the highest decline was predicted by inmcm4 model under RCP 4.5.

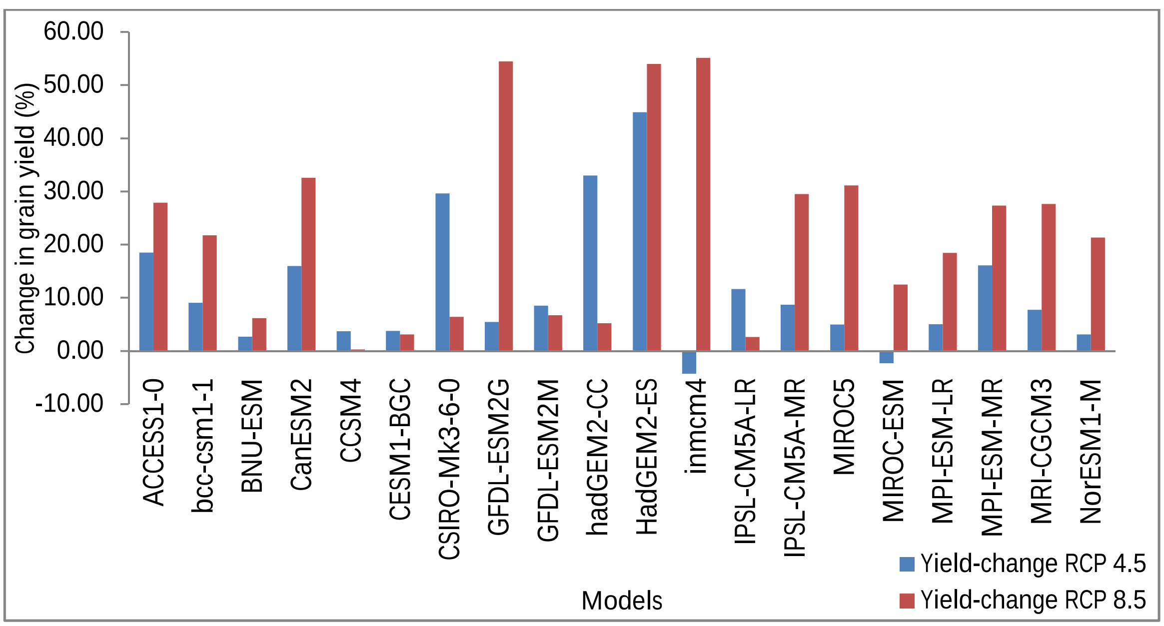


Figure 30: Impact of climate change on paddy rice grain yield in Kavumu catchment under RCP 4.5 and RCP 8.5 in mid-century

4.4.6 Impact of climate change on paddy rice grain yield in Kavumu catchment under RCP 4.5 and RCP 8.5 in end-century

The impact of climate change on paddy rice grain yield in Kavumu catchment under RCP 4.5 and RCP 8.5 in the end-century also varied from one model to the other (Figure 33). In all cases, the magnitude of positive change was greater under RCP 8.5 compared to RCP 4.5. All the models considered predicted an increase in yield ranging from 2.73 to 55.63% and from 33.07 to 69.36%, respectively, under RCP 4.5 and RCP 8.5. The highest increase was predicted under RCP 4.5 by the HadGEM2-ES model while the lowest was predicted by the IPSL-CM5A-LR model. For RCP 8.5, the highest increase was predicted by the MPI-ESM-LR model while the lowest was predicted by the NorESM1-M model.

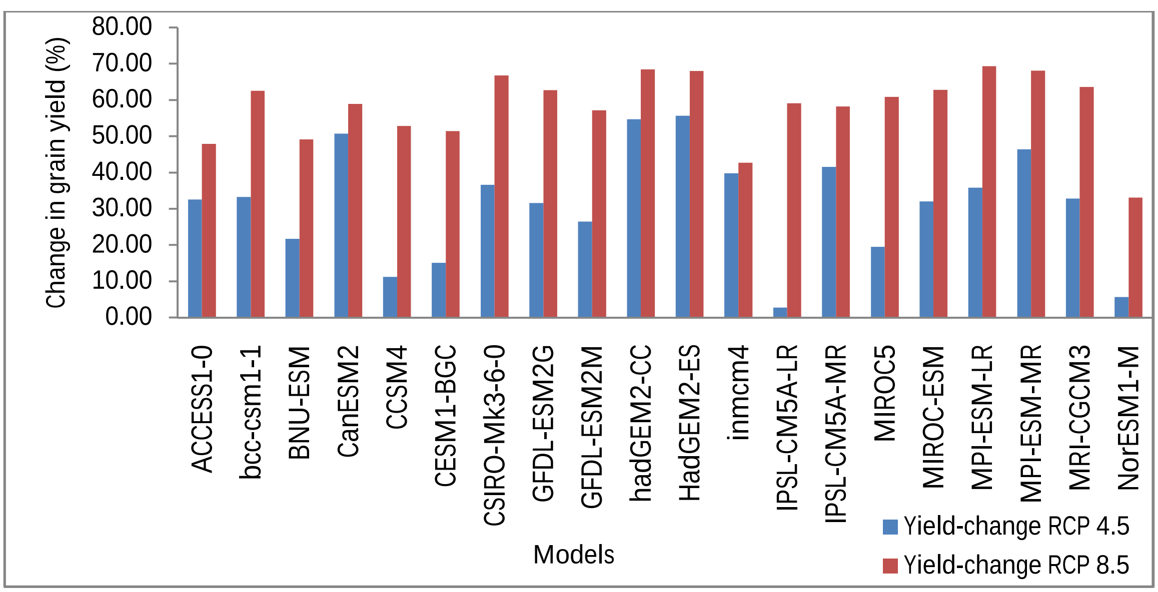


Figure 31: Impact of climate change on paddy rice grain yield in Kavumu catchment under RCP 4.5 and RCP 8.5 in end-century

4.4.7 Impact of climate change on paddy rice grain yield in Luberizi catchment under RCP 4.5 and RCP 8.5 in mid-century

The impact of climate change on paddy rice grain yield in Luberizi catchment under RCP 4.5 and RCP 8.5 in mid-century varied between the models (Figure 34). The majority of the models (60%) considered predicted small increases in grain yield ranging from 1.08 to 3.39% and from 0.38 to 3.78% respectively under RCP 4.5 and RCP 8.5. ACCESS1-0 predicted the highest declines under both scenarios (30.82% under RCP 4.5 and 32.43% under RCP 8.5). The rest of the models however predicted relatively smaller decreases ranging from 0.57 to 3.79% and from 0.46 to 5.36% respectively under RCP 4.5 and RCP 8.5.

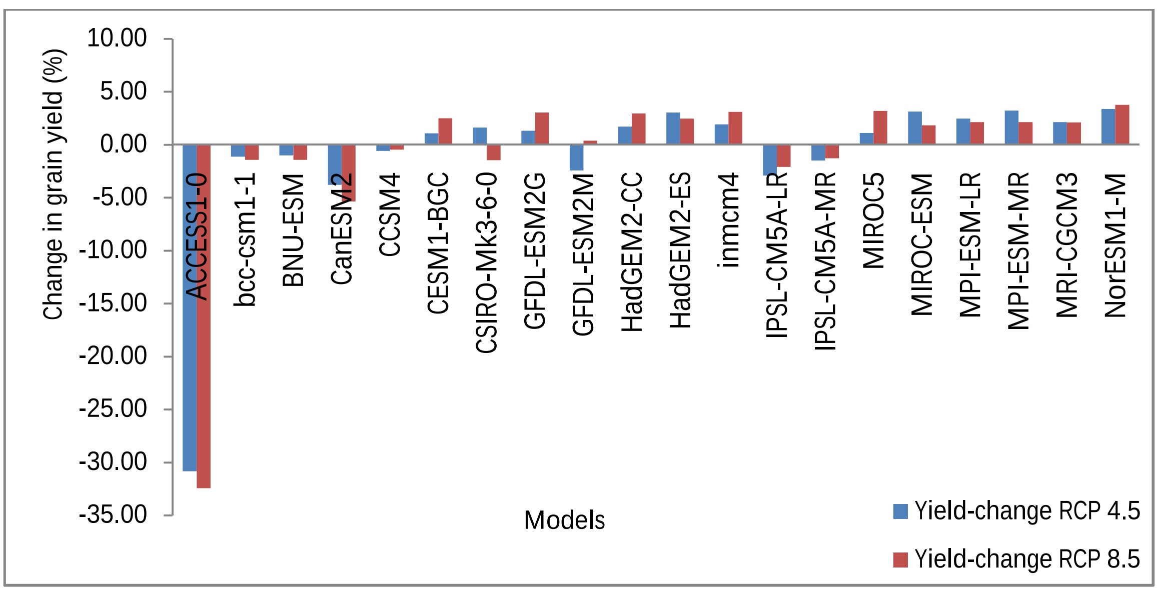


Figure 32: Impact of climate change on paddy rice grain yield in Luberizi catchment under RCP 4.5 and RCP 8.5 in mid-century

4.4.8 Impact of climate change on paddy rice grain yield in Luberizi catchment under RCP 4.5 and RCP 8.5 in end-century

Figure 35 presents the impact of climate change on paddy rice grain yield in Luberizi catchment under RCP 4.5 and RCP 8.5 in end-century. The magnitude of change varied between the models. Majority of the models (65 %) considered predicted small increases in grain yield ranging from 0.39 to 7.20% under RCP 4.5, while only 35% of the models predicted increases under RCP 8.5 ranging from 0.10 to 6.19%. Again, ACCESS1-0 predicted the highest declines under both scenarios (33.55% under RCP 4.5 and 39.08% under RCP 8.5), while the rest of the models predicted relatively smaller decreases ranging from 0.46 to 5.36% and from 1.16 to 13.66%, respectively, in the mid and end-centuries.

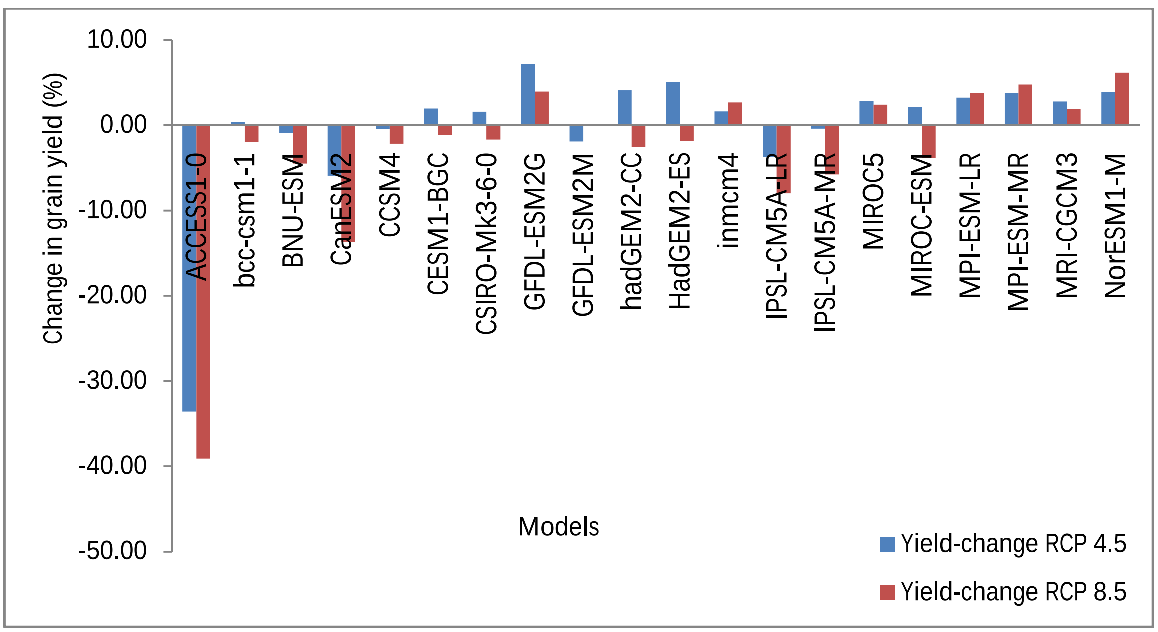


Figure 33: Impact of climate change on paddy rice grain yield in Luberizi catchment under RCP 4.5 and RCP 8.5 in end-century

CHAPTER FIVE: DISCUSSIONS

5.1 Assessment of the suitability of Kavumu and Luberizi catchments for paddy rice production

Generally, only a small portion of the two locations were at most moderately suitable for rice growth (7.51% and 18.07% of the catchment in Kavumu and Luberizi, respectively). In Kavumu catchment, the moderately suitable class was found in areas with abundant annual rainfall (<1300 mm), with no risk of erosion hazard because of the low slope (0-2%) and with enough soil nutrients (Figure A1, appendix1). Eighteen percent of Luberizi catchment was characterized as moderately suitable for rice production because the area had temperatures above 21°C, rainfall ranging between 1000 and 1300 mm, low risk of erosion (slope of 0-4%) and enough soil nutrient (Figure A2, appendix 2). The marginally suitable class represented 72.88% and 36.09% of the catchment in Kavumu and Luberizi, respectively. In Kavumu, this class was located in areas which receive enough rainfall (<1300 mm), with enough soil nutrients and low exposure to risk of erosion hazard (slope of 2-4%) but these areas had low temperatures (<18°C) and poor nutrient retention capacity (5<CEC<15 meq/100g) (Figure A2, appendix 2). In Luberizi, this class was located in the North-East and the South-West parts of the catchment. In the North-Eastern part, this class was found in areas with temperatures ranging from 20 to 30°C, with enough soil nutrients and rainfall ranging between 1000 and 1300 mm but with poor nutrient retention capacities (5<CEC<15 meq/100g) and/or high exposure to erosion hazard due to high slope (4-6%). In the South-Western part, this class was located in areas with rainfall ranging from 1000 to 1300 mm, with enough soil nutrients and exposed to low risk of erosion hazard (slope of 2-4%) but the poor nutrient retention capacity (5<CEC<15 meq/100g), and/or low temperatures (<18°C) of this area in relation to rice production make it marginally suitable (Figure A2, appendix A2). The unsuitable class covered 19.61% of the catchment in Kavumu and 45.84% in Luberizi (Figures 8 and 9). This is because both areas have low temperatures (<18°C), poor nutrient retention capacity (5<CEC<15 meq/100g) and high exposure to erosion hazard due to high slope (4-6%) (Figure A1 and A2, appendices 1 and 2).

These results are different from those of Kuria *et al.*, (2011) who, while considering soil properties (texture, sodicity and salinization) and landforms variables to assess the land suitability for rice cultivation in the Tana delta found out that the number of hectares available for each suitability class in the area was distributed as follows: 67% being highly to moderately suitable, 14% being moderately suitable, 10% being marginally suitable and about 9% of the study area was found to be unsuitable. Kihoro *et al.*, (2013) also in a similar study in the great Mwea region in Kenya, using soil (pH, drainage, humidity, texture), climate (temperature) and topography variables, found out that the number of hectares available to each suitability class was distributed as follows: 24.69% of the region was highly suitable, 47.45% was moderately suitable, 14.39% was marginally suitable and 13.48% was not suitable. Likewise, Dengiz, (2013) using soil (pH, N, P, K, Zn, drainage, texture, depth, surface stoniness, hydraulic conductivity, salinity) and topography variables to assess the land suitability in Çankırı-Kızılırmak district in the Central Anatolian region of Turkey, found out that the land highly and moderately suitable for rice cropping covered an area of about 837.3 ha (55.5%) while the unsuitable land covered 34% corresponding to adverse soil physical and chemical properties. The differences between our findings and those of the aforementioned studies could be explained by the number, the type and the quality of variables considered in the suitability analysis. In this study, variables including climate (rainfall and temperature), soil properties (pH, N, P, K, Organic carbon, CEC, texture) and topography were considered.

Generally, the most limiting factors identified in the Kavumu and Luberizi catchments were temperature, nutrient retention capacity and erosion hazard (Figures A1 and A2, appendices 1 and 2). In the entire Kavumu catchment and the South-western part of Luberizi catchment, temperatures were below 18°C. Low temperature stress was noted by Zhou *et al*., (2012) to be a common problem in rice cultivation and affects global production as a crucial factor. Rice is a cold-sensitive plant that originated from tropical or subtropical zones, therefore when low temperature occurs during the reproductive stages, it can cause serious yield components losses (Farrell *et al.*, 2006).

Exposure to cold temperature also affects all phenological stages of rice and lower grain production and yield. Low temperature in the vegetative stage can cause slow growth, reduce seedling vigor (Ali *et al.*, 2006), reduce tillering (Shimono *et al.*, 2002), increase plant mortality (Farrell *et al.*, 2006), and increase the growth period (Alvarado and Hernaiz, 2007). Low temperature in the range of 15–19°C during the reproductive stage impairs microspore development and causes the production of sterile pollen grains, resulting in poor grain filling and high spikelet sterility (Satake, 1976) and reducing spikelet fertility and affecting grain quality (Suh *et al.*, 2010).

In his study on low temperature tolerance in rice, Lee, (2001) found out, however, that rice varieties differ significantly in their capacity to tolerate low temperatures at various growth stages. From the research he made in 2000, he found that 57% of varieties released in Korea were highly tolerant to low temperatures. Suitable cultural practices like optimal application of nitrogen also seemed to improve cold tolerance in rice. Developing or introducing cold-tolerant varieties and suitable cultural practices is therefore of great importance because these will lead to consistently high yields in cold regions, particularly in the highlands and cooler regions. This could be one of the solution in the Kavumu catchment where low temperatures (<18°C) seem to be the most limiting factor making the biggest portion of the catchment marginally suitable for rice.

Both catchments don't have a good nutrient retention capacity (Figures A1 and A2, appendices 1 and 2). The poor nutrient retention capacity observed in both catchments could be attributed to the presence of ferralsols as major soil unit in the two catchments. Ferralsols have a texture varying from sandy loam to clay and are known to have a low and pH-dependent cation exchange capacity because they are dominated by low-activity clays (mainly kaolinite) and sesquioxides (Qafoku *et al.*, 2004). Furthermore, the soil analysis results (table A2, appendix 4) from the rice producing areas in both catchments indicated that the soil texture was composed of up to 70% of sand in Luberizi catchment and up to 46.5% of sand in Kavumu catchment; thereby explaining their low nutrient retention capacity. Kuria *et al.*, (2011) also found that unsuitable areas for rice cultivation where located in soils with a sandy clay texture with low water retention and high hydraulic conductivity.

Nutrient retention capacity of marginal soils can be improved through effective nutrient and water management. Application of large amounts of compost fertilizer was found by Soeun, (2010) to be one of the best practices for improving soil fertility and rice yield in areas where many cattles are raised. Combining mineral and organic fertilizers gives even better results; however, this has to be cost-effective to be easily adopted by farmers (Buri et al., 2012; Soeun, 2010).

Some parts of both Luberizi and Kavumu catchments are also exposed to erosion hazard. The erosion hazard in this study was obtained considering the soil texture and the topography (slope) of the catchments which varied from sandy to clayey and from 0 to 6% and above, respectively. The normal development of soils is closely related to the topography (slope) of the area, and the thickness of the soil layer decreases with increasing slope and increases with decreasing slope (Akinci *et al.*, 2013). Texture, on the other hand, is one of the most important parameters of soil and most of the physical properties of the soil depend upon the textural class (Halder, 2013). Slope degree and soil texture are therefore the main factors determining erosion control (Koulouri and Giourga, 2007) and highly influence the suitability of a given area for rice cultivation. This was observed by Kihoro *et al.*, (2013) who found that highly suitable areas were characterized by slope level of 0-2%, soil drainage imperfectly drained, a clay textural class and humidity levels >80, while the generally not suitable areas were located in mountainous areas with slope level >50%. Soil losses due to erosion reduce soil fertility by negatively affecting the physical, chemical and biological properties of soils. Lobo *et al.*, (2005) noted that erosion reduces the soil depth that is necessary for the development of plant roots and the amount of water that the plants need, decreases the content of nutritional elements and organic matter and consequently leads to the formation of soil that is unsuitable for cultivation. Also, the amount of materials carried away with erosion increases with the increasing degree of slope. Accordingly, the development of soils occurs slowly, with an increase in slope degree. Therefore, slope indirectly limits agricultural production by affecting soil properties negatively (Akinci *et al.*, 2013). Better water control and nutrient management are needed for a sustainable rice production in areas affected by erosion risk.

5.2 Trend analysis of historical climate and its impact on paddy rice production in Kavumu and Luberizi catchments

Annual and seasonal rainfall amounts in both catchments had a fluctuating but not significant trend from 1980 to 2010 while mean annual and seasonal temperature had a significant increasing trend in both catchments (Figures 10, 11, 12 and 13). During the same period, rice biomass significantly declined in the two catchments, while rice grain yield remained stable in Kavumu but significantly declined in Luberizi over time (Figures 14 and 15). The decline in grain yield and biomass over time could be attributed to the decline in soil fertility due to non use of fertilizers. According to Shisanya *et al.*, (2009), declining soil fertility arises from continuous cultivation where levels of soil replenishment, by whatever means, are too low to mitigate the process of soil nutrient mining, whereby the soil fertility is not restored by new inputs. It is a serious threat to agricultural productivity and was identified by Henao and Baanante, (2006) as a major cause of reduced crop yields and per capita food production in sub-Saharan Africa.

5.3 Characterization of projected climate in Kavumu and Luberizi catchments

In both sites, most of the models predicted an increase in rainfall and temperature (Tables 7 and 8). The magnitude of the change varied from one model to the other and from one period to another. These results are in line with those by Rimi *et al.*, (2009) who in their study on trend analysis of climate change and investigation on its probable impacts on rice production at Satkhira in Bangladesh using three different models (GFDLTR, UKTR and HadCM2) found out that all the models predicted an increase in temperature. Only one model (HadCM2) predicted an increase in rainfall. They also found that the magnitude of change in temperature and rainfall varied with the model and the period.

By comparing the two sites, the increment in rainfall amount is likely to be relatively higher for Kavumu; while the increment in maximum temperature is likely to be relatively higher in Luberizi (Tables 7 and 8). This could be because Kavumu catchment is located on a higher altitude (1500m) with colder temperatures compared to Luberizi catchment, which is in a lowland (altitude: 773- 1000m) with hotter temperatures. The relationship between elevation, precipitation and temperature is complex. However, it is generally recognized that rainfall increases with altitude while temperature decreases simultaneously. Subarna *et al.*, (2014) noted, in their study on the relationship between monthly rainfall and elevation in the Cisangkuy watershed Bandung regency in Indonesia, that there is a strong relationship between monthly rainfall and elevation with average correlation coefficient equal to 89%. They found that increase in rainfall with elevation has a mean slope value of 11.62 mm for every increase of 100 m elevation. Garcia-Martino *et al.*, (1996) working on rainfall, runoff and elevation relationships in the Luquillo Mountains of Puerto Rico characterized by a subtropical maritime climate also found a significant relationship between elevation and mean annual rainfall as well as elevation and the average number of days per year without rainfall. A comparison of rainfall patterns between a high and a low elevation station indicated that annual and seasonal variations in rainfall are similar along the elevational gradient. However, the upper elevation station had greater annual mean rainfall (4436 mm/yr compared to 3524 mm/yr) while the lower station had a greater variation in daily, monthly, and annual totals. On the other hand, Wang *et al.*, (2011) when analyzing the effect of altitude and latitude on surface air temperature across the Qinghai-Tibet Plateau in China found that there is a gradual decrease in temperature with increasing altitude and latitude.

As far as climate change is concerned, our findings are in line with those by Herrero *et al.*, (2010) who in their study on climate variability and climate change and their impacts on Kenya's agricultural sector found that the coastal and lowland regions are likely to become drier, while the highlands and Northern Kenya are likely to become wetter. They are as well similar to Gwimbi *et al.*, (2012) who when using the CSIRO model to project future climate in Lesotho also found that temperature will increase from 1 to 2°C throughout the country by 2050, with lower increases in mountainous and highland zones. The model further projected a significant decrease in rainfall (between 50mm and 100mm annually) in the lowlands and foothills, with little change in the mountains. Our findings are also consistent with FAO, (2008) projections according to which, it is expected that temperate regions (wet areas) could become wetter and dry areas in the tropics could become drier (FAO, 2008).

5.4 Impact of climate change on biomass and grain yield in Kavumu and Luberizi catchments

In Kavumu catchment, rice biomass and grain yield are projected to increase with climate change. However, the magnitude of the enhancement will vary depending on the period and the scenario considered. In contrast, in Luberizi catchment, all the models predicted a decline in biomass while grain yield is projected to slightly increase except for the end-century under RCP 8.5 where the majority of the models considered predicted a decrease.

Grain yield enhancement in Kavumu catchment is mostly attributed to the combined effect of the increase in temperature and rainfall as can be noted by the positive relationship between grain yield and temperature ($p<0.01$) and between grain yield and rainfall ($p<0.01$). However, change in biomass was not related to temperature ($p>0.05$) nor to rainfall ($p>0.56$). The low temperatures found in the Kavumu catchment were found to be a limiting factor to rice production and that could be the reason why each increment in temperature had a direct positive impact on grain yield. Increase in rainfall on the other hand improved water availability. In Luberizi catchment, the situation was different. There was a negative relationship between biomass and temperature ($p<0.001$) and between biomass and rainfall ($p<0.01$). The decline in biomass was more closely related to temperature than to rainfall. However, no clear pattern was found between grain yield and the climatic parameters. In Luberizi catchment, in fact, the average daily temperature (23.96°C) at the baseline was already within the optimum range for rice production before any change in climate is considered.

According to Stansel and Fries, (1980), for a 120-day rice variety, the average daily temperature during the 55 day-long vegetative period should be around 22°C and the temperature during the reproductive period (about 21 days) should be around 24°C. Harvest occurs following an approximate 35-day period of grain filling and maturation corresponding to an average daily temperature of 24°C. This could explain the projected decrease in biomass in Luberizi catchment on one hand and the inconsiderable increase in grain yield followed by a decline in the end-century under RCP 8.5, on the other hand in both catchments. Biomass and yield decline in Luberizi catchment and in Kavumu catchment in the end-century under RCP 8.5 could be mostly associated with shortening of the growth duration, decrease in sink formation, increase in maintenance respiration (Matthews and Wassmann, 2003) and high-temperature-induced spikelet sterility (Matsui *et al.*, 1997).

Ritchie, (1993) in his study on Genetic specific data for crop modeling explained that the rate of biomass accumulation is determined by the photosynthetic rate minus the respiration rate. Higher temperature shortens the rice growth period; consequently reducing the period available for photosynthetic accumulation. Hence, biomass accumulation is greatly influenced by the ambient air temperature. Bachelet and Gay, (1993), further stated that, the acceleration of the development process of the crop due to temperature increase leading to shortening of the growth duration, results at the same time in most cases in incomplete grain filling and therefore reductions in yield. Stigter and Winarto, (2013) recently found in their study on rice and climate change that temperatures beyond critical thresholds not only reduce the growth duration of the rice crop, they also increase spikelet sterility, reduce grain-filling duration, and enhance respiratory losses, resulting in lower yields and lower-quality rice grain.

In addition to quantitative effects on yields, high temperature levels are also, as stated by Wassmann and Dobermann, (2007), likely to affect grain quality although the impact pathways are not yet clear. One characteristic of poor grain quality is the high chalk content mainly because chalky grains break during milling and thus, decrease the yield of edible rice (Wassmann and Dobermann, 2007).

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In light of the above results and discussions it can be concluded that:

Kavumu and Luberizi catchments cover 1744 ha and 16036 ha, respectively but generally only a small portion of the two locations is at most moderately suitable for rice growth (7.51% and approximately 20% of the catchment in Kavumu and Luberizi, respectively). Marginally suitable class represented 72.88% and 36.09% of the catchment in Kavumu and Luberizi respectively. The most limiting factors to rice production in both catchments were temperature, nutrient retention capacity and erosion hazard.

During the last 30 years (1980-2010), rice biomass significantly ($p<0.001$) declined in both catchments. Rice grain yield however, remained significantly stable in Kavumu but significantly declined in Luberizi.

Both rice biomass and grain yield are projected to increase with climate change in Kavumu, except for the end-century under RCP 8.5, while in Luberizi, there was a decline in rice biomass and a slight increase in rice grain yield followed by a decline in the end-century under RCP 8.5.

6.2 Recommendations

It can be recommended that:

-Moderately and marginally suitable areas should be used for rice production. However, cold tolerant rice varieties together with suitable cultural practices need to be introduced in the Kavumu catchment while effective nutrient and water management need to be applied in the Luberizi catchment in order to boost rice production in the two areas

-Both organic and inorganic fertilizers should be used to stabilize rice production in the two study areas

-Rice farmers and decision makers should be sensitized in order to take advantage of the weather induced benefits which are projected in the Kavumu catchment so as to increase rice production.

-Appropriate adaptation strategies should be planned and disseminated in the Luberizi catchment which is projected to be more sensitive than the Kavumu catchment to future climate change

-The APSIM model should be used to test the efficiency of the existing climate change adaptation measures in rice yield

-The downscaled climate information should also be used to assess the impacts of climate change on other crops and other sectors

-More factors including biophysical, environmental and socio-economic variables should be integrated in the future land evaluation for accurate assessment. Impact of climate change on land suitability can also be assessed.

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APPENDICES

Appendix 1

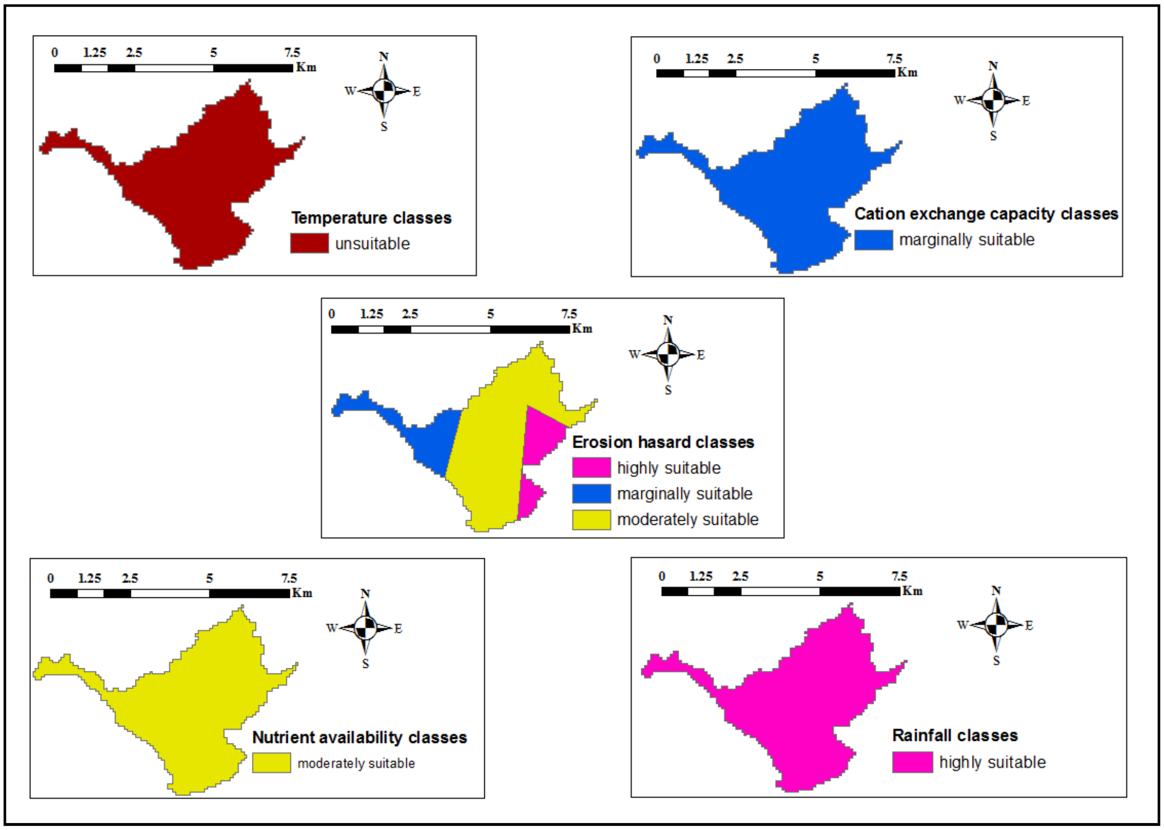

Figure A1: Parameters considered in suitability analysis in Kavumu catchment

Appendix 2

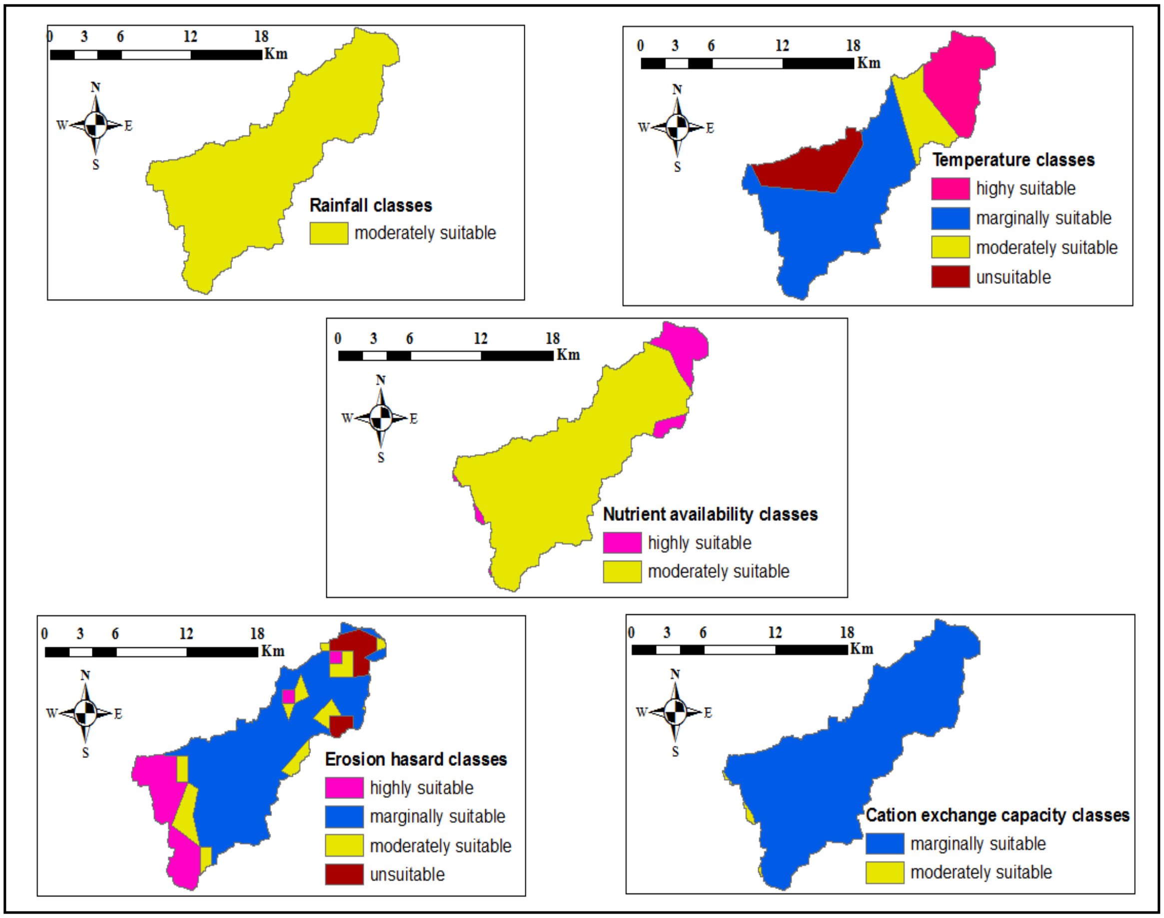

Figure A2: Parameters considered in suitability analysis in Luberizi catchment

Appendix 3

Table A1: Mean values of selected water quality parameters in Kavumu and Luberizi catchments

Site	Parameters	Mean	Minimum	Maximum	Standard deviation
Kavumu	pH	6.85	6.4	7.2	0.29
	Electrical conductivity(µS/cm)	189.53	179.7	198.15	7.17
	HCO_3^- (meq/L)	1.19	0.71	2.03	0.41
	Na (meq/L)	0.19	0.15	0.22	0.02
	Ca^{2+}+Mg^{2+} (meq/L)	3.3	1	5.6	1.32
	SAR	0.16	0.13	0.27	0.04
	RSC (meq/L)	-2.11	-3.97	-0.19	1.21
Luberizi	pH	7.52	7.09	7.75	0.18
	Electrical conductivity(µS/cm)	49.01	43.55	55.8	3.33
	HCO_3^- (meq/L)	0.88	0.41	1.22	0.24
	Na (meq/L)	0.17	0.14	0.21	0.02
	Ca^{2+}+Mg^{2+} (meq/L)	1.21	0.7	1.73	0.34
	SAR	0.23	0.17	0.4	0.06
	RSC (meq/L)	-0.23	-0.94	0.42	0.46

Appendix 4

Table A2: Soil analysis results for Kavumu and Luberizi catchments

Site	Depth	pH	OC (%)	N (ppm)	K (cmol/Kg)	P (ppm)	CEC (cmol/Kg)	Ca (cmol/Kg)	Mg (cmol/Kg)	Mn (ppm)	EC (ds/m)	B (ppm)	Al (cmol/Kg)	Clay (%)	Sand (%)	Silt (%)
Kavumu	20	4.54	3.77	3000	0.26	6.59	11.07	2.44	1.2	60.35	0.16	0.09	23.27	33.61	46.54	22.43
	40	4.41	3.63	2833	0.17	3.48	7.8	1.44	0.77	38.07	0.13	0.07	24.67	31.6	38.66	20.09
Luberizi	20	6.76	2.07	1900	0.62	5.28	14.37	7.55	2.55	56.25	-	-	-	12.45	70.76	12.7
	40	6.1	1.52	1300	0.92	11.01	14.69	6.11	2.46	63.42	-	-	-	12.25	72.61	12.33

Source: Université Catholique de Bukavu laboratory, 2013