UNIVERSITY OF NAIROBI

MAPPING POTENTIAL RISK OF EXPOSURE TO HEAT STRESS FOR DAIRY CATTLE UNDER CURRENT AND FUTURE PROJECTED CLIMATIC CONDITIONS IN UGANDA

BY

JOHN YUMBYA MUTUA
I58/62250/2013

A thesis submitted in partial fulfilment for the award of the degree of Master of Climate Change Adaptation of the University of Nairobi

2022

DECLARATION

This thesis was written by me and in my own words, except quotations from published and unpublished sources which are indicated and acknowledged as such. I am conscious that the incorporation of material from other works or a paraphrase of such material without acknowledgement will be treated as plagiarism, subject to the custom and usage of the subject, according to the University Regulations on Conduct of Examinations. The source of any picture, map or other illustration is also indicated, as is the source, published or unpublished, of any material not resulting from my experimentation, observation, or specimen-collecting.

Signature Date: 09//07/2022

John Yumbya Mutua
I58/62250/2013
Department of M
University of Nairobi

This thesis is submitted for examination with our approval as research supervisors:

Prof. Charles K.K. Gachene Signature: Date: 11/07/2022
Department of Land Resource Management and Agricultural Technology
University of Nairobi

Dr. Mohammed Yahya Said Signature: Date: 12/07/2022
Department of Earth and Climate Sciences
University of Nairobi

DEDICATION

I dedicate this work to Dr Dionysius (Dan) Kiambi who introduced me to agricultural research.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my thesis supervisors Prof. Charles Gachene and Dr Mohammed Said, Department of Earth and Climate Sciences (ECS), The University of Nairobi, for the continuous support of my master's study and related research, their patience, motivation, and immense knowledge.

This work would not have been possible without the financial support from the Alliance of Bioversity International and CIAT through the framework of the Environment Flagship of the CGIAR Research Program (CRP) on Livestock. I am especially indebted to Ms An Maria Omer Notenbaert, and Dr Birthe Katharina Paul who have been supportive and worked actively to provide me with the time and resources to pursue this study.

Nobody has been more important to me in the pursuit of my studies than members of my family. I would like to thank my parents, whose love and guidance are with me in whatever I lay my hands on. My brothers who are my greatest cheerleaders and most importantly, I wish to thank my loving and supportive wife, Faith, and my sons Felix and Justin, who provide unending inspiration.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

CGIAR	Consultative Group on International Agricultural Research
CIAT	International Center for Tropical Agriculture
CMIP	Climate Model Intercomparison Project
CORDEX	Coordinated Regional climate Downscaling Experiment
CRP	CGIAR Research Programme
DDA	Uganda's Dairy Development Authority
ECMWF	European Centre for Medium-Range Weather Forecasts
ECS	Earth and Climate Sciences
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GCF	Green Climate Fund
GCMs	General Circulation Models
GHGs	Greenhouse Gases
GIS	Geoinformation Systems
GLW	Gridded Livestock of the World
ILRI	International Livestock Research Institute
IPCC	Intergovernmental Panel on Climate Change
MAAIF	Ministry of Agriculture, Animal Industry and Fisheries
NASA	National Aeronautics and Space Administration
NCCP	National Climate Change Policy
NGO	Non-governmental organization
RCP	Representative Concentration Pathway
SMHI	Swedish Meteorological and Hydrologic Institute
SRTM	Shuttle Radar Topography Mission
THI	Temperature-Humidity Index
UBOS	Uganda Bureau of Statistics
UON	University of Nairobi

DEFINITION OF TERMS

Heat stress	A situation when an animal's heat uptake from the environment and metabolism exceeds its heat loss through radiation, convection, evaporation, and conduction.
Exposure	The presence of livestock in places that could be adversely affected by a heat stress.
Adaptation	Adjustments by smallholder dairy farmers in response to actual or expected heat stress and their effects or impacts on livestock.
Resilience	The capacity of smallholder dairy farmers to cope with a heat stress for dairy cattle in ways that maintain its production at farm level.
Dairy value chain	Entire chain of actions involved in the production of milk from the farm to the consumer.

ABSTRACT

Heat stress is a major stressor of dairy livestock production nearly everywhere in the globe, and it is only going to get worse as the world gets warmer. The aim of the study was to map areas where dairy cattle are susceptible to experiencing heat stress under current and future projected climatic conditions in Uganda. The specific objectives included (i) Investigate the trend of heat stress for dairy cattle during the current and future periods, (ii) Map areas and dairy cattle are at risk of exposure to heat stress under current and future climate conditions, and (iii) Determine adaptation strategies and options for the impact of heat stress across the dairy value chain. The study follows a transdisciplinary approach by leveraging geoinformation techniques. Using ERA-Interim reanalysis dataset for the historical period (1981-2010) and for two periods in the future (2021-2050 and 2071-2100) climate predictions of ten global circulation models (GCMs) under Representative Concentration Pathways (RCPs) 4.5 and 8.5 emission scenarios. This study demonstrates a significant rise in the historical prevalence of severe heat stress in dairy cattle ($p<0.05$) over time in 38 percent of the country. Much of the significant rise is concentrated in the country's northern and central regions. Under future climate conditions, simulations under both RCP scenarios predicted that the country would gradually deteriorate to increasingly severe conditions. On average, milk decline due to heat stress is anticipated to be 2.3 and 15.6 kg milk/year/dairy cow for 2021-2050 and 2071-2100 respectively based on RCP 8.5. Even though dairy farmers are already adapting to heat stress, future heat stress management techniques will necessitate informed climate smart technologies aiming at embedding resilience in current dairy production systems. The findings of this study are concerning, mainly because they show that the effects of heat stress have a substantial effect on Uganda's dairy production systems. The results can be utilized to assist stakeholders in the livestock industry in creating policies that are supported by data and planning, as well as to direct resource allocation in the industry toward the development of adaptable and flexible production systems that can survive future heat stress.

CHAPTER 1: INTRODUCTION

1.1: Introduction

The livestock sector benefits over a billion people throughout the world and will continue to be vital in the next decades (FAO, 2009). The sector is key to smallholders as a source of income. Animal-derived foods are important nutrient sources, accounting for 18 percent and 40 percent of total energy and protein consumption, respectively, on a worldwide scale (ILRI, 2019). Moreover by 2050, global livestock product's demand is expected to twofold (Rojas-Downing et al., 2017). Despite stagnant productivity, the sector is quickly emerging in developing countries due to rising demand for animal-sourced products (Thornton, 2010). Studies have however shown that in some countries especially Europe and the USA, the decline in productivity for exotic cattle is linked to heat stress (Fodor et al., 2018; Gunn et al., 2019).

In its Fifth Assessment Report (AR5), the United Nations Intergovernmental Panel on Climate Change (IPCC) stated unequivocally that the Earth's climate is warming. The global average surface temperature increased by about 0.6 degrees Celsius throughout the twentieth century (IPCC, 2014). Temperatures in Uganda are expected to rise soon by 1.8°C and 2.1°C by 2050s based on Representative Concentration Pathways (RCP) 4.5 and 8.5 respectively and in the range of 2.2°C and 4.0°C by 2080s based on RCPs 4.5 and 8.5 respectively (Egeru et al., 2019). Climate change is one of the many stressors on livestock production systems (Rojas-Downing et al., 2017), more so in the tropics and subtropics where the majority of the world's ruminants are found (Herrero et al., 2012). Heat stress is caused by temperature and humidity variations that are above the comfort zone usually above 22° C, 25° C, and 28° C at 100%, 50% and 20% for maximum temperature and relative humidity respectively. It can damage cattle, affecting their output and performance, as well as increasing mortality rates (Kadzere et al., 2002).

Heat stress conditions in livestock occur when an animal cannot dissipate enough heat to maintain a thermal equilibrium in the body, causing physiological disorders that adversely affect the animals' productive output. According to previous studies, the combination of temperature shifts and increasing frequency of heatwaves cause heat stress affecting livestock production by decreasing feed intake which in turn causes reduced milk production (Hahn et al., 1997; Wayman et al., 1962).

Different dairy cattle breeds, on the other hand, have varying degrees of heat stress resistance (Carabaño et al., 2019). The rising heat tolerance standard measures include physiological functions such as regulating body temperature and breathing rate. The shift of the dairy production system to a market-oriented model with exotic varieties may lead to a relative heat stress trade-off under present and future climate change. If climate change continues to progress as expected, the negative impacts of heat stress on dairy cattle productivity will worsen. The purpose of this research is to map areas where dairy cattle are susceptible to experiencing heat stress in Uganda now and in the future, as well as to investigate the implications for adaptation planning across the dairy value chain.

1.2: Problem Statement

Uganda's dairy industry is one of Africa's fastest growing. By 2018, the country had more than two billion liters of milk produced (UBOS, 2019). The industry is quickly changing as a result of rising demand for animal products, though production has stagnated (Thornton, 2010). This is due to the climate that is changing affecting livestock production by reducing water resources, decreasing the quantity and quality of forages and feed, increasing prevalence to livestock diseases and heat stress which in turn has impact on milk production (Rojas-Downing et al., 2017). Trade-offs regarding heat stress under current and future climate change may result from the conversion of dairy production systems to market-oriented models with exotic breeds. Additionally, one of the climate shocks to which Ugandan farmers must adjust is the threat that heat stress poses to dairy animals (Thornton et al., 2019). Despite the importance of thermal heat stress on dairy cattle, little is reported on the current period evaluation and future changes in heat stress conditions in Uganda. The adverse impacts of heat stress on dairy production would worsen if climate change continued as expected. This study aimed at mapping areas where dairy cattle are susceptible to experiencing heat stress over the current period (1981-2010) and project the future (2021-2050) using ten (10) GCMs in Uganda, under RCP 4.5 and 8.5. It also explored the options to respond and/ or adapt to the changing heat stress risk.

1.3: Research Questions

The following questions were addressed by this research project:

i. What is the trend of heat stress for dairy cattle during the current and future periods?

H1: Heat stress has been increasing historically and will increase in the future.

ii. In which areas are dairy cattle most vulnerable to heat stress under current and future climate conditions?

H1: Dairy cattle in the cattle corridor is likely to be exposed to heat stress.

iii. Which adaptation strategies and options are available to combat the impact of heat stress across the dairy value chain?

H1: Smallholder farmers are already adapting to heat stress at farm level.

1.4: Objectives

The aim of the study was to map areas where dairy cattle are susceptible to experiencing heat stress under current and future projected climatic conditions in Uganda. Specific objectives included: -

i. Investigate the trend of heat stress for dairy cattle during the current and future periods.
ii. Map areas where dairy cattle are at risk of exposure to heat stress under current and future climate conditions.
iii. Determine adaptation strategies and options for the impact of heat stress across the dairy value chain.

1.5: Justification and Significance of the Research

In Uganda, the livestock sector is driven mainly by the dairy industry. The sector has maintained an average growth of about 8% per annum since 1990 (Tijjani & Yetişemiyen, 2015). The transformation is mainly happening by farmers adopting improved breeds that guarantee high milk production (Kabunga et al., 2017). Under present and future climate change, however, this might result in compromises regarding heat stress. If climate change persists as expected, the negative effects of heat stress on Uganda's dairy cattle production will intensify.

The major impediments in sound policy development in the dairy sector in Uganda are lack of data to aid in decision making (Staal & Kaguongo, 2003). Decisions on sustainable livestock production systems require robust methodologies that can accurately identify and track changes both climate and human-driven in the dairy sector. Although there are initiatives in place led by Uganda's Dairy Development Authority (DDA) to address problems in the sector production is far below the country's potential.

Despite the importance of thermal heat stress on dairy cattle, little is reported on the current period evaluation and future changes in heat stress conditions in Uganda. This research aimed at mapping areas where dairy cattle are susceptible to experiencing heat stress under current and future projected climatic conditions in Uganda. This data is crucial for Uganda as it prepares for the effects of climate change to guide agricultural extension and policy.

1.7: Scope of Research

This research study focused on dairy production systems in Uganda through mapping risk of exposure to heat stress for dairy cattle under current and projected future climatic conditions. Although farm management factors such as livestock housing influence the actual heat stress an animal experience, the danger of heat stress in dairy cows was the subject of this study and should not be considered as an assessment of actual heat stress at the farm level. The research examined the effect of heat stress on the dairy value chain through a consultative stakeholder heat stress assessment process with the aim of identifying present and future heat stress adaptation strategies.

1.8: Overview of the Methodology

The study used a transdisciplinary approach to evaluate heat stress trends for dairy cattle and monitor dairy cattle currently under heat stress, and those at risk in the future based on projected future climate conditions, using geoinformation systems (GIS) spatial modeling procedures and statistical analysis using R software version 3.5.3 "Great Truth" (R Core Team, 2019). A stakeholder consultation on heat stress assessment was conducted in the month of March 2020 in Uganda to allow participants to explore the modelled maps and identify ongoing and potential heat stress adaptation options. The outcome from the workshop were summarized using descriptive statistics.

CHAPTER 2: LITERATURE REVIEW

2.1: Global dairy production systems

Livestock play a significant role in the world economy by providing food in the form of milk and meat, traction and transportation for animals, manure for agricultural use, monetary gain from the selling of livestock-related goods, and acts as a capital investment for sale and use during misfortunes and harsh times. Global milk production was estimated at 843 million tonnes as of 2018, this was an increase of 2.2 percent from 2017. Higher dairy herd numbers in India and Pakistan, more effective production processes in Turkey, and improved output per cow in both in the United States and the European Union, among other factors in other geographies, are all contributing to the growth of the dairy industry (FAO, 2018). Furthermore, global demand for dairy products has increased significantly in recent decades, owing to a combination of rising population and greater economic development in developing countries. Climate change has, however, exacerbated both global and local implications on dairy production in recent years (Gauly & Ammer, 2020). In the developed world, the housing of high-yielding breeds that are prone to heat stress has been modified to improve the animals' ability to cope with heat stress conditions (Hempel et al., 2019).

2.2: Regional dairy production systems

East African dairy production systems are generally categorised into three types, intensive, semi-intensive and extensive systems. Production systems are varied in terms of feeding, size of operation (grazing systems are the most prevalent), pastoralist and agro-pastoralist systems, and farmer breeds. In Sub-Saharan Africa, cattle grazing on natural pastures provide 75 percent of the milk. Farmers are embracing high-yielding dairy breeds that were created for temperate climates. In the tropics, extreme temperatures, heat stress, and a lack of proper feeds have a significant impact on these breeds (Hernández-Castellano et al., 2019). However, there is ongoing research to adapt these breeds to the new environments for example through crossbreeding to increase tolerance (Kim & Rothschild, 2014). This has also been identified as one of the adaptation strategies for dairy production systems in Kenya (Watende, 2016). To maintain optimal dairy production, traits to look for in while cross breeding include increased milk production, maintaining reproduction, and increased health in the tropics (Cooke et al., 2020). However, these advancements have a bleak future since the extent of future climate change and heat stress is predicted to render livestock production in extensive systems less viable (Clark et al., 2020).

2.3: Dairy production systems in Uganda

Cattle is Uganda's main source of milk, though goats, camels and buffaloes also contribute to milk production (Balikowa, 2011). Small-scale farmers are the majority owners of the cattle population (Tijjani & Yetişemiyen, 2015). The country's most popular indigenous cattle are the Ankole and East African Shorthorn Zebu, they account for 93 percent of the population (MAAIF/UBOS, 2010). Friesian Holsteins and their crosses, as well as local breeds like the Nganda, Nkedi, and Kyoga, are among the breeds kept (Mugisha et al., 2014). Dairy regions in Uganda are defined by agro-ecological zones. These regions show significant differences in milk production. Mbarara area located in the southwest part of the country produces a significant amount of the total milk production (Ekou, 2014), a recent report estimates production to 100,000 litres per day (Wangalwa et al., 2016). The North and Eastern regions lag other regions in term of production.

There are various categorizations of dairy production systems in Uganda. Initially, a study by Seré & Steinfeld (1996) categorised livestock production systems into grasslands, rainfed mixed farming, irrigated mixed farming and communal systems. The production systems were further classified into intensive, semi-intensive, and extensive dairy systems by MAAIF/ILRI (1996) by considering farm management and capital investment. Kasirye (2003) thereafter differentiated four systems based on feeding strategies i.e., free ranging, paddocking, communal grazing, and zero-grazing systems. Notenbaert et al. (2009) adapted the map by Seré & Steinfeld (1996) and produced the most recent classification which includes four categories i.e. extensive, intensive, agro-pastoral/ pastoral and other systems. In Uganda, foreign breeds of cows are commonly kept in intensive systems and/or zero-grazing herds, with most of them being Holstein Friesian breed (Grimaud et al., 2004). As of 2017, annual national milk output stood at 1.6 billion litres (Uganda Bureau of Statistics, 2018). According to the Uganda Dairy Development Authority, 80% of Ugandan milk is sold, with the remaining 20% consumed by farmers.

2.4: Climate change and livestock

Climate change is defined as the long-term alteration in the climate's current state that may be recognized by variations in the mean and/or variability of its attributes (IPCC, 2018). This is due to interactions between the atmosphere and various geologic, chemical, biological, and geographic elements within the Earth system as well as periodic variations in Earth's climate brought on by changes in the atmosphere. It can lead to prolonged warm/hot seasons characterized by intense radiation energy extended for a longer period and increased relative humidity (Fabris et al., 2019), this greatly affects the livestock sector. The livestock industry is responsible for 14.5 percent of worldwide greenhouse gas (GHG) emissions, mostly nitrous oxide, and methane (Gerber et al., 2013). Both are generated through the disposal of manure while enteric fermentation is the main source of methane. The bulk of these emissions are from ruminant livestock kept by pastoralists. Livestock in these systems feed on poor quality feed which is associated with higher greenhouse gas emissions. As of 2016, greenhouse gas emissions from the Uganda livestock corridor were 2009 Gg CO2-eq per year, with grazing systems producing 88.5 percent of the total GHG emissions (Kiggundu et al., 2019).

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Uganda's climate has evolved during the last 50 years, with seasonal mean temperatures rising. By the 2060s, average temperatures are anticipated to rise by 1 to 3 degrees Celsius, and by 1.4 to 4.9 degrees Celsius towards the end of the twenty first century (McSweeney et al., 2007), the same trend in increases in the range of 2 to 4 degrees Celsius are expected in Europe (Cardoso et al., 2019). Climate change has a significant influence on cattle and the ecosystem commodities and services that they rely on. Directly, it induces heat stress in the animals, which leads to changes in their behavioural and metabolic habits, such as reduced feed intake (Kadzere et al., 2002), increased energy requirement, decreased conception rate (Seif et al., 1979). Indirectly, it causes increased water demand by animals and decreased water supply (Thornton et al., 2009), changes in pathogen growth, vector dispersion, and disease transmission rates have resulted in increased pest and disease pressure, biodiversity losses, both in terms of habitat loss, plants and animals, and a smaller gene pool for future adaptation, are frequently associated with diminished disease resistance, changes in feed resource amount, quality, and composition, as well as overall system productivity and livelihood patterns. And they are all interacting (and frequently worsening) one another. Climate change, on the other hand, has been shown in some studies to have positive effects on animal feed, such as lower transpiration, which enhances plant water use efficiency (Rötter & van de Geijn, 1999). In 2015, Uganda's Cabinet approved the National Climate Change Policy (NCCP), which lays out Uganda's long-term climate change mitigation and adaptation policies throughout all sectors of the economy (Ministry of Water and Environment, 2015).

2.5: Risk of exposure to heat stress for dairy cattle

Heat stress occurs when the environmental temperatures elevate and the animals lack the ability to conduct thermoregulation or even maintain their normal body temperatures (Hahn, 1997). The combination of heat and humidity causes heat stress, which adversely affects animal performance. Heat stress makes cooling through metabolism a difficult process. This is because the atmosphere is already near saturation and hence sweating is compromised due to extreme heat. The cow's body temperature, therefore, escalates on a temporal basis, affecting its intake and general performance abilities. Due to a reduced gut defence mechanism, heat stress can also result in a higher risk of secondary bacterial infections (Pearce et al., 2013).

Heat stress has numerous profound effects on dairy cattle, some of which involve lactation and reproductive performance (Lemerle & Goddard, 1986). Heat stress prolongs the gestation period of dairy cows compared to cooler conditions (Tao & Xin, 2003), this is because of heat stress-induced changes in feed consumption patterns. When dairy cows are subjected to moderate heat stress for more than four days, their dry matter intake and milk yield drop by 48 percent and 53 percent, respectively (Garner et al., 2017). However, animals suffering heat stress obtain various mechanisms of coping with the situation, e.g., some dissipate heat through increasing respiration rate, metabolic reactions (sweating), escalated pulse and increased rectal temperature; with all of these indicating the animal's tolerance level in variable climatic conditions. Different livestock and breeds have different heat tolerance degrees as reported by previous research findings (Muller & Botha, 1993), however exotic breeds are more vulnerable to heat stress than native breeds (Mutua et al., 2020; Taye et al., 2017).

Heat stress events for diverse livestock species in the Caribbean were assessed by Lallo et al. (2018), who found that ruminants will be subjected to higher heat stress in the future than in the past, posing a threat to their productivity. For the case of dairy breeds, Das et al. (2016) observed that because dairy animals produce more metabolic heat than beef cattle, they are more susceptible to heat stress. According to Nesamvuni et al. (2012), dairy cattle in most parts of South Africa are expected to endure severe stress in the future due to rising forecasted temperatures. The mammary glands of dairy cows are stimulated by heat stress, which affects milk output (Fabris et al., 2019), and it brings forth many uncalculated losses related to heat stress-induced occurrences. Heat stress is a major constraint to livestock production in the tropical and subtropical belt, including Uganda (Thornton et al., 2019). It wields a huge blow to the dairy farming economic situation, by negatively affecting milk production. Heat stress tolerance limit for Friesian Holsten cattle in Europe has been provided as 60 to 78, although for most exotic dairy cattle milk losses start at 60 to 72 (Bohmanova et al., 2007). However, management practices at farm level matter (Thornton et al., 2021). Heat stress tolerance limits and how dairy cattle responds have been provided in Table 3.2.

2.6: Implications for adaptation

Climate change vulnerability in Uganda is high due to the high dependence on livestock for income, food, nutrition. Further, the livestock systems are highly reliant on rainfed forages which in addition to continuous poverty, the ability to adjust is limited (Kirui et al., 2015). Farmers' perception of changing climate is consistent with historical climatic trends (Mubiru et al., 2018). Recent studies have called for policy implementation at household level through provision of agricultural extension services on climate adaptation practices (Twecan et al., 2022). Some of these adaptation measure might include keeping heat stress tolerant dairy breeds, use of appropriate sheds which are easy to clean and well aerated and use of milk tankers that are insulated to transport milk during the day amongst others as listed in Chapter 4, section 4.4.3. Policymakers can take use of existing and novel ways for dealing with and adapting to heat stress. All stakeholders must rally behind the adoption of coping and adapting measures if the government and commercial players are to achieve the ambitious goals of sustainably empowering smallholder farmers and boosting their revenues.

2.7: Mapping heat stress risk

Heat stress indicators depend on the temperature, relative humidity and/or wind speed associated with an animal's discomfort during exposure (Bishop-Williams et al., 2016). Previous studies have mapped heat stress on other livestock breeds using weather information obtained from remote sensing data Uganda (Mutua et al., 2020). Heat stress-causing environmental factors are studied using the temperature-humidity index (THI), a measurement that combines the effects of ambient temperature and relative humidity. Thom, (1959) introduced it to quantify the severity of heat stress in people. Currently, there exists several

THI equations as shown in Table 2.1 that have been adapted to describe thermal conditions that drive heat stress in livestock in different regions (Berman et al., 2016; Bianca, 1962; Bohmanova et al., 2007; Cargill & Stewart, 1966; Kelly CF, 1971; Lallo et al., 2018; National Research Council, 1971; Thom, 1959; Yousef, 1985).

Table 2:1: List of Thermal Humidity Index equations

THI equations	**Livestock type**	**Reference**
$THI1 = (1.8 \times Tdb + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times Tdb - 26.8)]$	All Livestock	National Research Council (1971)
$THI2 = (Tdb + Twb) \times 0.72 + 40.6$	All Livestock	National Research Council (1971)
$THI3 = Tdb + (0.36 \times Tdb) + 41.2$	All Livestock	National Research Council (1971)
$THI4 = (Tdb \times 0.15) + (Twb \times 0.85)$	Ayrshire cattle	Bianca (1962)
$THI5 = (Tdb \times 0.35) + (Twb \times 0.65)$	Jersey, and Holstein-Friesian cattle	Barrada (1957)
$THI6 = 3.43 + (1.058 \times Tdb) - (0.293 \times RH) + (0.0164 \times Tdb \times RH) + 35.7$	Holstein-Friesian cattle	Berman et al. (2016)

More recently, the equations have been adapted for assessing heat stress on various livestock species for example as shown in studies conducted on chicken (Tao & Xin, 2003), and swine (Zumbach et al., 2008). In Uganda, the current common exotic breed promoted by the dairy farmers is the black and white Holstein-Friesian. Ndor Fodor et al. (2018) investigated the association between the temperature-humidity index and Holstein-Friesian cattle milk output using an 11-member climate projection ensemble and observed robust relationships between THI and milk production.

CHAPTER 3: METHODOLOGY

3.1: Location

Uganda is situated in East Africa, along the equator. It covers approximately 241,551 square kilometres, 16 percent of which are open water and swamps (Figure 3.1). Uganda is bordered on the east by Kenya, Tanzania on the south, Rwanda, and the Democratic Republic of Congo on the west, and South Sudan on the north. The lowest elevation is 614 meters at Albert Nile at the border with South Sudan while the highest is 5,111 meters at Margherita Peak on Mount Stanley. Agriculture is the country's principal source of income.

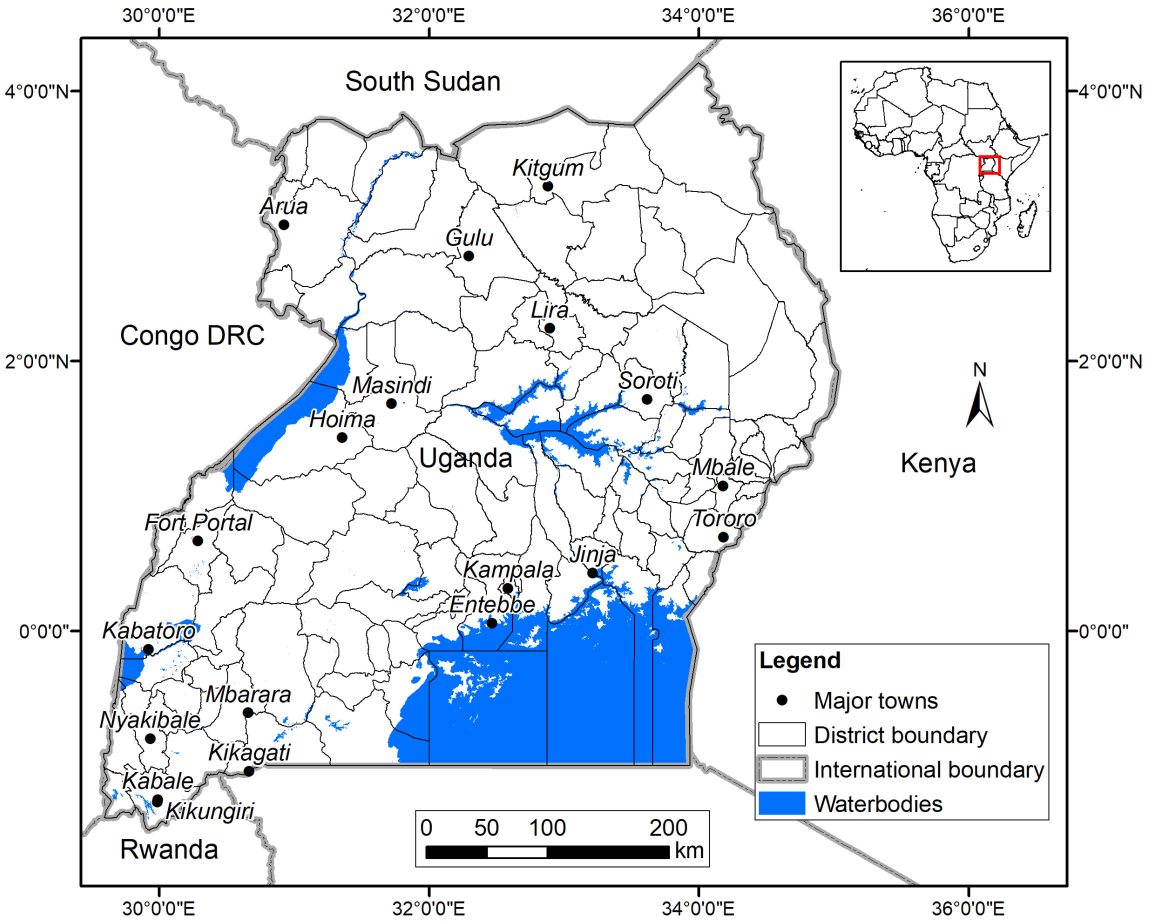

Figure 3.1: Map of the study area. Data sourced as follows: Boundaries from https://gadm.org, waterbodies from https://www.hydrosheds.org, and major towns from https://www.naturalearthdata.com

3.2: Biophysical Setting

3.2.1: Climate

Uganda is generally characterized by the warm tropical climate, and the temperatures normally range of 29°C. The minimum and maximum temperature range from 18°C to 31°C and 15°C to 23°C respectively. However, like any other tropical region, temperature varies from one location to another. The high-altitude regions, e.g., Mount Elgon is cooler and highly humid compared to the lower regions. Despite the relatively moderate to slightly high temperatures in the lower regions during the daytime, the temperatures normally fall to accommodative 16°C to 18°C during the evenings, and even cooler during the night. The warmest time of the year is from December to February, while the hottest period is from March to May, with June and July portions. As one of the countries experiencing the oscillatory effects of the Inter-Tropical Convergence Zone, Uganda receives winds from the Atlantic Ocean to the west and the Indian Ocean to the east and dry north-east / south-east monsoon. The country's northern regions receive unimodal rainfall, whereas the central, western, and eastern regions experience bimodal rainfall (Nandozi et al., 2012). The annual rainfall varies between 500 and 2500 mm. The long rainy season lasts from March to May, whereas the short rainy season lasts from September to November (Nsubuga et al., 2014).

3.2.2: Vegetation

The country has a wide spectrum of biodiverse vegetation. However, the vegetation is unevenly distributed with southern Uganda being densely vegetated, while the central and northern regions mainly comprising wooded savannah (Mwanjalolo et al., 2018). There is an adverse variety of vegetation types in the southern region. The most abundant vegetation in the central and northern regions are Elephant grass and the Candelabra trees. The Candelabra trees are unpalatable due to their toxicity (Botha & Penrith, 2008). The tree causes dermal irritations on skin contact, tracheal discomfort if ingested, and blindness if in contact with the eyes. The Elephant grass is a perennial native grass species that are characterized by low nutrient and water requirements. It is an indicator of the climatic conditions at which they occur. There is also tropical forest, acacia woodlands, riparian forests, bushy thickets, montane forests, marshes, and other wetland vegetation. The diverse vegetation is classified according to the three major regions: Lake Basin, highland, and the northern region (Figure 1).

3.2.3: Land Uses and Resources

There are various land uses that cut across different economic requirements. The most common is agriculture. The agricultural system mainly supports maize, millet, cassavas, sweet potatoes, plantains, groundnuts, and beans as the subsistence crops. The most popular cash crops include coffee, tea, cotton, and tobacco. Agriculture is Uganda's largest employer, employing nearly 70% of the country's workforce and contributing 23.5 percent to the country's GDP (Uganda Bureau of Statistics, 2018). Other than crop production, they also practice livestock production widely, both dairy farming, meat, and fish production. There are various resources that facilitate these land-use practices; from forests, natural water bodies (e.g., Lake Victoria and River Nile), man-made water pans, wetlands, etc. all of which are rich in ecological functions.

3.2.4: Physiography and Drainage

The country has various physiography ranging from mountains, rivers, lakes, and wetlands. They all play key roles in the ecological service provision towards the people of Uganda. Lake Victoria in the southeast and Lake Albert in the west are two large lakes whose importance cannot be overstated. The Albert Nile (west to north flow) and Victoria Nile (southeast to north flow) are among the main rivers that are connected to other tributaries that supply water across the country. The mountains Elgon (east), Stanley and Ruwenzori are amongst the major mountains in Uganda, each with an explicable contribution. They also act as the major watersheds which facilitate the drainage of ground or surface water from regions of high elevation to regions of low elevation. It ensures that water occurring from precipitation as is expected in the future (Olaka et al., 2019), is reserved for present and future use in livestock production.

3.2.5: Water Resources

The country has various water reservoirs and channels, especially the southern and western regions. Watersheds in the different regions channel rainwater from high altitude regions to low altitude regions where it is stored. Figure 3.2 shows river network and inland water bodies in the country.

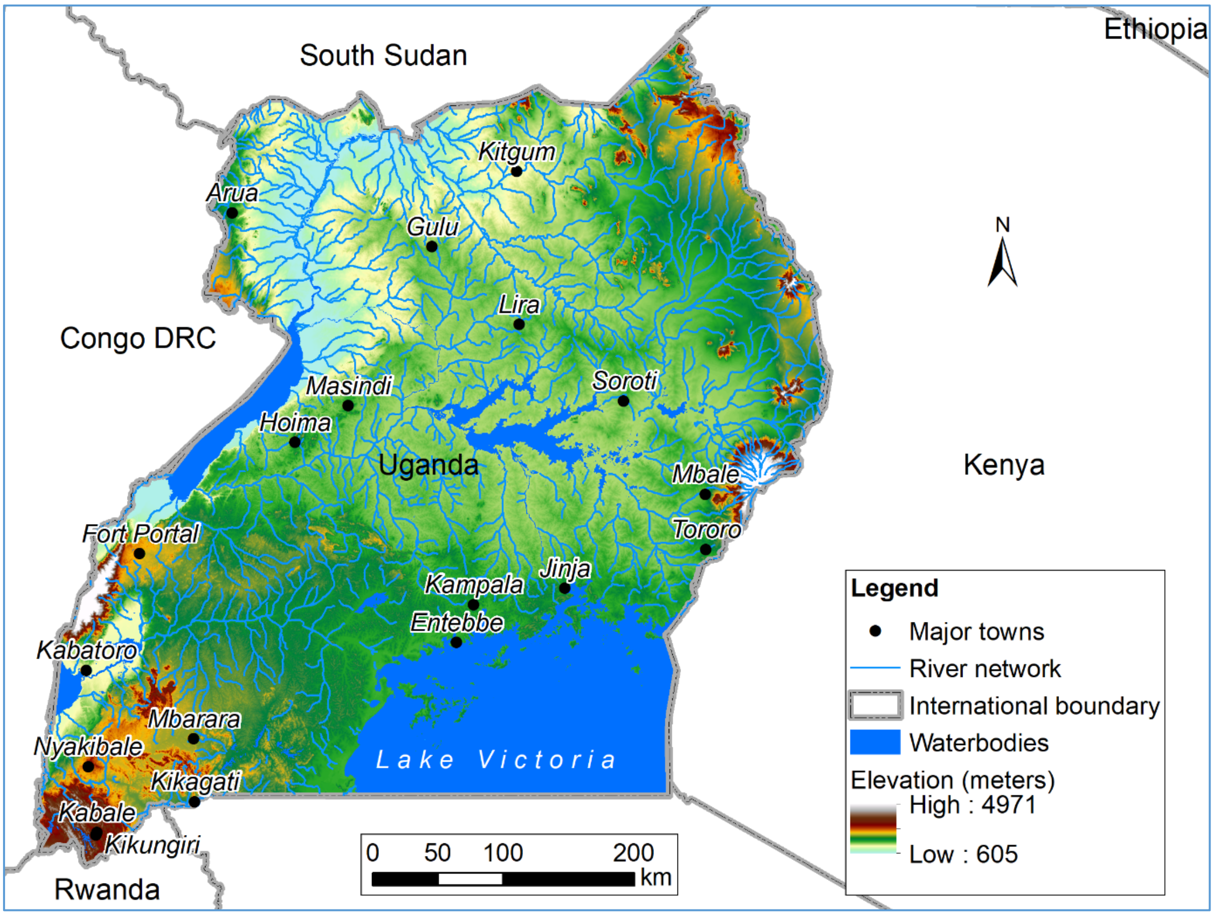

Figure 3.2: River network and inland waterbodies in Uganda. Data sourced as follows: Rivers and waterbodies from https://www.hydrosheds.org, and elevation from National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM) Version 3.0

During the process, the water interacts with anthropogenic activities, which either negatively or positively affect the quality that is received downstream. In regions where the human population is clustered, the quality of both ground and surface water is highly adulterated. The urban regions are characterized by highly pollution rates; both organic and inorganic pollutants, point and nonpoint sources. In the rural regions where agriculture is the major economic activity, a high number of organic inputs and some aspect of inorganic inputs find their way into either ground or surface water. In groundwater, acidity and toxicity levels are raised (Bakyayita et al., 2019), and this may cause harm to animals that encounter the borehole water. In surface water, eutrophication and sedimentation resulting from anthropogenic activities negatively affect water quality.

3.2.6: Biophysical Vulnerabilities

Uganda is in the tropics and closer to the Indian and Pacific oceans, and to a lesser degree the Atlantic Ocean. These water bodies experiences changes in sea surface temperatures which have a significant impact on the amount and timing of yearly rainfall in the country. Temporal changes have seen different land-use practices influence the resilience of the Ugandan ecosystems (Mwanjalolo et al., 2018). In the past years, the ecosystems were self-sustained with high resilience levels. Climate change has made different agroecosystems in this regions to suffer (Jiang et al., 2014). Moreover, different farming practices (Kiggundu et al., 2019), and global greenhouse gas emissions have slowly made various ecosystems highly susceptible to failure due to climate change. Furthermore, many small-scale farmers like any other in the region reside in marginal climate zones, and their livelihoods are reliant on climate-sensitive resources. This is no different compared to Kenya for example where pastoralists communities depend on climate sensitive natural resources for their provisions and production needs (Kaoga et al., 2021). The costs of restoration are unfavourable for the people whose majority still dwindle in extreme poverty.

3.3: Socio-economic Setting

3.3.1: Social Setting

The country's human population was estimated to be 42 million in 2018 and is increasing at a 3.7 percent annual rate. The population density is 213 persons per square kilometre (World Bank, 2018). By 2050, the population is projected to be the second largest in East Africa, at 100 million. Demographically, the female population overwhelms the male population at 50.71 percent and 49.29 percent, respectively. At present, 70 per cent of the workforce is working in agriculture.

3.3.2: Animal Health Setting

The country being a subtropical region, there is a variety of health hazards and diseases experienced in this region. There are number of animal diseases that have for a long period constrained livestock production in the country (Eisler et al., 2007). The most prevalent diseases include east coast fever (Muhanguzi et al., 2014), lumpy skin (Ochwo et al., 2018) and clinical mastitis (Byaruhanga et al., 2017), which has been reported to reduce milk production by up to 60 percent (Anri, 2012). These diseases have been reported across the country. There are no estimates of the economic losses of any of the outbreaks that have occurred in Uganda. The Ugandan government liberalized the supply of veterinary services, which has resulted in a plethora of actors involved, making control and oversight of service provision challenging (Ilukor et al., 2015).

3.3.3: Livestock Production Systems

In 2019, the cattle sector provided around 3.5 percent of the total national GDP (UBOS, 2019), and about 58 percent of the population relies on it for their livelihood (FAO, 2019). In 2018, Uganda had approximately 14.6 million cattle (UBOS, 2019), with most of the population concentrated in the northern and central regions (Figure 3.3). The country produced 2.04 billion litres of milk as compared to 1.614 billion litres that were produced in 2017 (UBOS, 2019). This is attributed to improved market access and extension services mostly provided through cooperatives (Arinaitwe & Baluka, 2019).

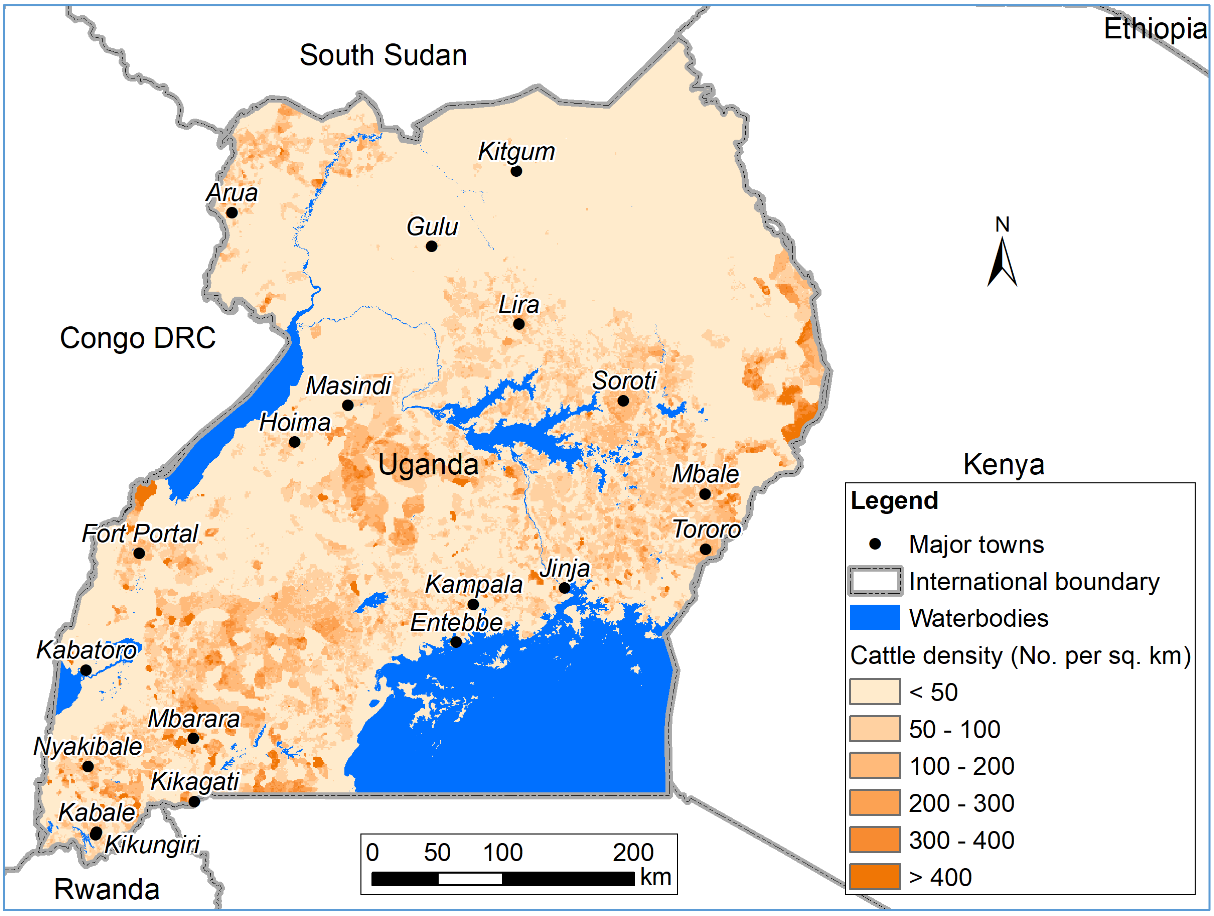

Figure 3.3: Cattle distribution in Uganda. Cattle density data sourced from the Livestock Geo-Wiki (http://www.livestock.geo-wiki.org)

The humid and sub-humid zones, where rainfed crop-livestock systems predominate, are home to the majority of the country's greatest livestock production region (Figure 3.4). Mixed rainfed systems can be found in temperate and tropical highland zones throughout the country's southern and western regions. The northern regions are mostly composed of rangeland-based livestock-only systems.

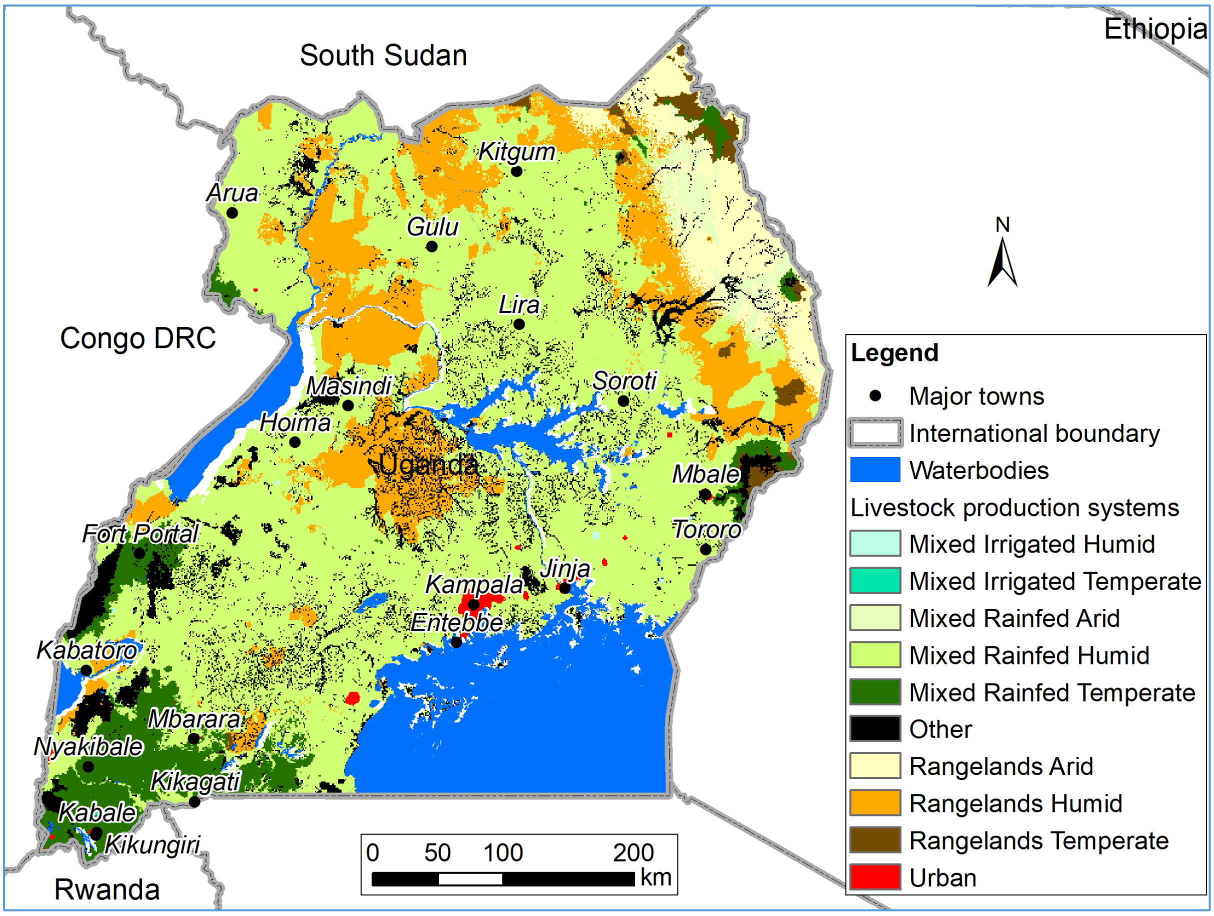

Figure 3.4: Livestock production systems in Uganda. Data sourced from Robinson et al. (2014)

3.3.4: Regulatory Framework

Local governments play a critical part in Uganda's agricultural sector's success. These institutions, on the other hand, have flaws in terms of collective decision-making and scrutiny of various regulatory frameworks, particularly rules managing agricultural industries (Ministry of Agriculture Animal Industry and Fisheries, 2011). Many failed structures and slow technological adoption are due to primarily weak regulatory frameworks (Ampaire et al., 2017a). Over the last two decades, there has been a series of policy changes in the dairy sector that have resulted in increased production (ILRI, 2007). The policy changes were anchored in the Plan for Modernisation of Agriculture (PMA) which set to provide training, advocacy, and marketing to dairy farmers across the country.

3.3.5: Sensitivity to Climate Change

Despite being the least likely to contribute to increased GHG emissions in the past, socio-economically disadvantaged communities that include most of the smallholder farmers are often the worst affected by climate change in Uganda (Atube et al., 2021). The socio-economic activities of these communities are extremely sensitive and vulnerable to climate change (Magrath, 2008). This is because most of the population is reliant on natural resources for their livelihood. While many smallholder farmers are affected by climatic occurrences on a regular basis, their limited access to and control over resources makes them less equipped to cope with shocks and stressors. In addition, they overly depend on natural resources for their livelihood, thus whenever there is some strain in ecological functions, the human population is affected. Due to a lack of local coping capacity, minor hazards such as reduced, or lack of rainfall can turn into humanitarian emergencies (Quandt, 2021).

3.4: Conceptual Framework

The framework (Figure 3.5) for assessing the risk of heat stress in dairy cattle in Uganda under current and future climate circumstances depicts the interplay between the environment and the dairy production system. When utilized in a holistic manner to assess the risk of heat stress in dairy cattle, a transdisciplinary approach is taken whereby the interaction between the climate system and dairy production system is investigated through biophysical mapping and a stakeholder engagement is conducted to develop adaptation options. Below is a description of the five components: -

i. Climate system: Climate-related stresses include reduced precipitation, increased temperature, and increased relative humidity.
ii. Livestock production system: non-climatic trends, on the other hand, include technological advancement and a growing livestock population.
iii. Stakeholder engagement: All stakeholders were brought together to discuss and understand the impacts of heat stress to develop adaption options.
iv. Heat stress mapping: Stakeholder engagement was backed by scientific evidence from heat stress mapping.
v. Adaptation option planning: The above components guided the process of formulating adaption options in the livestock sector that can be communicated efficiently.

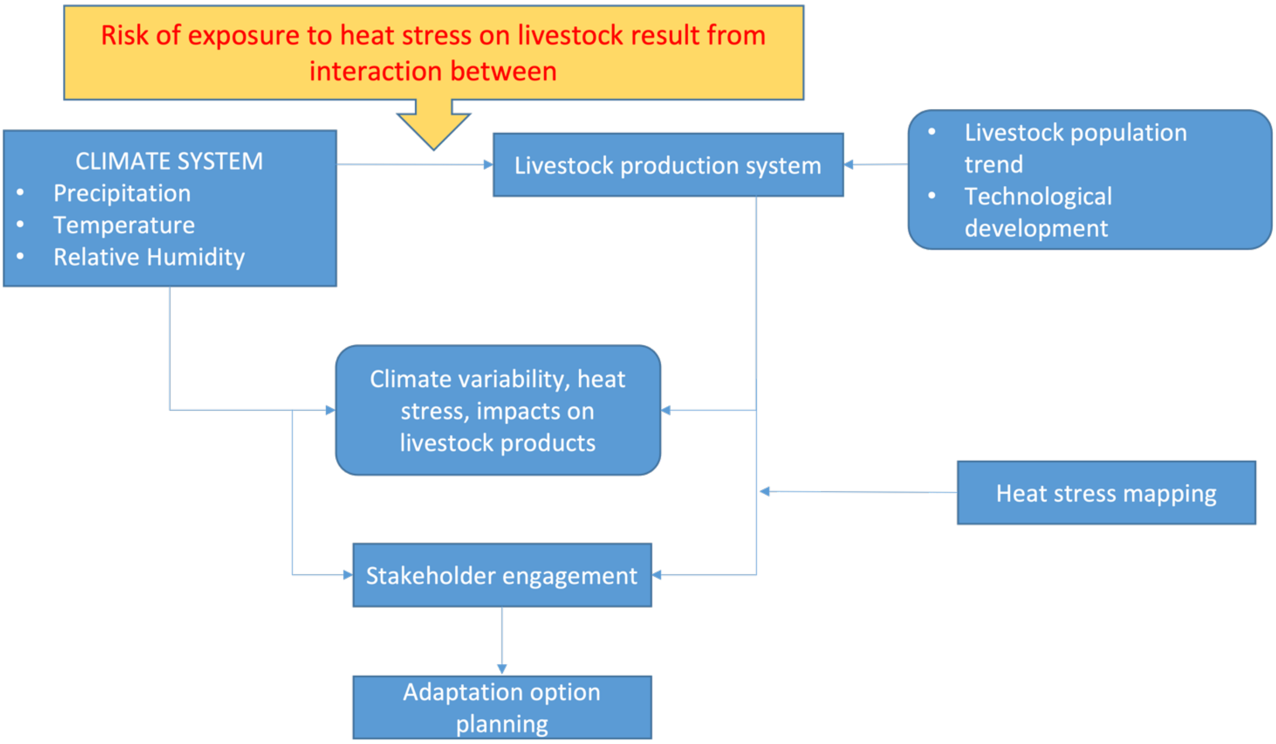

Figure 3.5: Conceptual framework

3.5: Methods

3.5.1: Methodology for Objective 1

Objective: Investigate the trend of heat stress for dairy cattle during the current and future periods.

Weather data, including relative humidity and maximum temperature, was gathered on a daily basis from the National Oceanic and Atmospheric Administration (NOAA)- National Climatic Data Center (NNDC) (http://www7.ncdc.noaa.gov/CDO/dataproduct) and TuTiempo.net repository (http://en.tutiempo.net/) for use in accuracy testing of the ERA-Interim reanalysis dataset and multi-model ensemble GCMs in simulating Thermal Humidity Index (THI). The twelve synoptic stations utilized in this study have a consistent spatial distribution and can be used to represent various climate zones in Uganda.

The ERA-Interim reanalysis gridded dataset that included daily temperature and relative humidity daily data and used for simulating current period (1981-2010) was provided by the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011), while the Coordinated Regional climate Downscaling Experiment, hereafter referred to as CORDEX gridded dataset that included daily temperature and relative humidity data are used for simulating future periods (2021-2050 and 2071-2100), at a spatial resolution of 50 km is supplied by the Swedish Meteorological and Hydrologic Institute (SMHI). The data is downscaled using the Rossby Centre regional climate model-RCA4 model and the Climate Model Intercomparison Project (CMIP5) as boundary conditions, as well as the GCMs specified in Table 3.1. All the data used in this study is freely available in online repositories.

Table 3:1: List of the global circulation models (GCMs) that were employed in the research

GCM	**Modelling group, country**	**Reference**
CCCma-CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	Chylek et al. (2011)
CNRM-CM5	National Centre for Meteorological Research, France	Voldoire et al. (2013)
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation, Australia	Collier et al. (2011)
EC-EARTH v2-2	European Centre for Medium-Range Weather Forecasts, United Kingdom	Hazeleger et al. (2011)
IPSL-CM5A-MR	Institute Pierre Simon Laplace, France	Dufresne et al. (2013)
MIROC-MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), Japan	Watanabe et al. (2010)
HadGEM2-ES	Met Office Hadley Centre, United Kingdom	Jones et al. (2011)
MPI-ESM-LR	Max - Planck - Institute for Meteorology, Germany	Giorgetta et al. (2013)
NCC-NorESM1-M	Norwegian Climate Centre, Norway	Bentsen et al. (2013)
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory, USA	Dunne et al. (2013)

Three criteria were used to select the models; (i) maximum temperature and relative humidity data were available on a daily basis, (ii) over Uganda, models have a spatial resolution of less than 50 kilometres, and (iii) in terms of regional representation of essential features of observed climate, models perform well when compared to other GCMs (Kisembe et al., 2019). The simulations for the future are based on RCP 4.5, an optimistic scenario that provides a framework for assessing climatic implications in the future with stable radiative forcing, and RCP 8.5, a pessimistic scenario that considers a future with more carbon emissions (IPCC, 2014b).

Data Analysis

The daily time series datasets for observed, ERA-Interim reanalysis, and multi-model ensemble GCMs (Table 2) were aggregated into monthly time series by calculating the average of daily means per month using R software version 3.5.3 "Great Truth (R Core Team, 2019). Because no THI equation has been devised for the various dairy cattle breeds and climates which is found in Uganda, THI was computed based on the widely utilized equation for different animals in tropical and sub-tropical regions, equation 1 (National Research Council, 1971). This equation was used for the historical period. The result was a spider chart showing agreement between the results of THI calculations for the three datasets for different months over Uganda.

$$THI = (1.8 \times Tdb + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times Tdb - 26.8)] \qquad \text{Equation 1}$$

Where:

Tdb = dry-bulb temperature in degrees Celsius.

RH = relative humidity in percent.

In this study, following Lallo et al. (2018) and Vitali et al. (2009), the daily maximum temperature is used instead of dry-bulb temperature. The above equation has previously shown reasonably good performance for the Holstein-Friesian breed and in different regions. Following the calculation of the THI value for each day, the likelihood of each THI category as defined by Collier et al. (2012), for current and future climate conditions was calculated. - THI categories and thresholds for categorizing daily THI levels and their reaction in dairy cattle are presented in Table 3.2.

Table 3:2: THI categories and thresholds for categorizing daily THI levels and their reaction in dairy cattle

Threshold	Category	Animal Response
THI ≤ 72	*Normal*	i. The performance of both the productive and reproductive systems is at its peak.
72 > THI ≤ 79	*Mild*	i. Animal hides under shade. ii. Rectal temperature increases. iii. Breathing rate increases and blood vessels dilate.
79 > THI ≤ 89	*Moderate*	i. The body's temperature rises, and reproductive effectiveness suffers. ii. Breathing rate significantly increases. iii. Feed intake decreases. iv. Significant increase in water consumption.
THI > 89	*Severe and Danger*	i. Increase in breathing rate and saliva production. ii. Decrease in reproductive performance. iii. Decrease in rumination and urination. Reproductive performances are severely affected. iv. Heat stress is quite severe, and animals may die as a result.

A daily average of maximum temperature and relative humidity for all GCMs was calculated for the current period and per RCP and period for the future period using overlay analysis. The technique allows the combination of characteristics of several datasets into one. The method was implemented using the raster package (Hijmans, 2017) in R software version 3.5.3 "Great Truth" (R Core Team, 2019). The result was one raster layer per variable, day, and period. Following that, the daily THI value of each grid cell was determined using the methods provided by the National Research Council (1971).

Ultimately, the probability of each THI category for current and future climate conditions is estimated based on equation 2, and the results were averaged per period (averages over a 30 - year period).

$$P(Di) = n/N+1 \qquad \text{Equation 2}$$

Where:

n: No. of THI category events in a year.

N: number of days in a year.

For both periods i.e., current and future, trends in severe heat stress were detected by applying a Mann-Kendall test (Mann, 1945). First, utilizing the above-mentioned frequency of extreme heat stress, the slope was calculated to get the direction and magnitude of trends. Next, the p-value was extracted to see which trends are significant and finally, pixels with values less than 0.05 were masked out from the trend map, to only report the significant change in THI at a 95 percent confidence level.

3.5.2: Methodology for Objective 2

Objective: Map areas where dairy cattle are at risk of exposure to heat stress under current and future climate conditions.

To further understand the dairy production methods and livestock numbers in the study area, a full desktop study was done. Cattle density geospatial data was sourced from the Gridded Livestock of the World (GLW 3) database (Gilbert et al., 2018; Robinson et al., 2014). This is the latest harmonized data for the subnational distribution of livestock as of 2010. The dataset was created using machine-learning techniques at a spatial resolution of one kilometre and it is also available for other livestock species and has been updated to suit official Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) sub-national estimations. The information was obtained from the Livestock Geo-Wiki website (https://www.livestock.geo-wiki.org). To further differentiate dairy cattle from the larger database of cattle, statistics from the MAAIF/UBOS (2010), that shows the proportions of exotic-dairy cattle by districts in Uganda were applied on the cattle dataset to produce a dairy cattle density geospatial layer. To estimate the impact on milk production, a global dataset provided by the FAO Global Perspective Studies Unit was used. The dataset includes milk production estimates for the years 2000 to 2030, as well as absolute and proportional changes at a spatial resolution of 0.05 degrees (Robinson & Pozzi, 2011). This analysis was conducted in the intensive production regions as mapped by (Robinson et al., 2014).

Data Analysis

Using R software version 3.5.3 "Great Truth", the long-term mean THI for the historical period was calculated using the results obtained in Section 3.3 showing the daily THI per pixel. As indicated in Table 3.2, each pixel was then categorized using the criteria used to categorize THI values based on their reaction in dairy cow. Next, the categorised THI layer was overlaid with the dairy cattle population spatial data for estimation and quantification of dairy cattle population at risk. The result was the population of dairy cattle under the various classes of THI. Heat stress has an impact on milk supply at different periods of lactation, and earlier research has suggested that milk production remains constant until it exceeds a particular threshold, for example, above the mild heat stress threshold, under pastoral management, milk output in Zebu cattle drops by 0.099 kg milk per day each THI unit, and production diminishes as heat stress increases. In this study, the daily milk loss values for each grid cell were determined using a milk loss function proposed by Bohmanova et al. (2007), and as indicated in equation 3.

$$ML = max(THI_d - THI_{thr}, 0) \times 0.099 \qquad \text{Equation 3}$$

Where:

ML: Milk loss per kilogramme per year per dairy cow.

THI_d: Daily thermal humidity index.

THI_{thr}: Above a certain temperature, milk output drops by 0.099 kg milk per day each THI unit.

The result was milk production at risk of change under future climate circumstances, due to the frequency, ferocity, and length of moderate and severe heat stress conditions.

3.5.3: Methodology for Objective 3

Objective: Determine adaptation strategies and options for the impact of heat stress across the dairy value chain.

Desktop Study

A desk review of current policy papers was carried out, with a particular focus on those targeted at prioritizing the execution of climate change action plans and strategies in the livestock sector. The purpose was to find policy gaps in heat stress in dairy production systems.

Field Work

A stakeholder workshop was held in March 2020 to explore relevant context-specific adaptation methods for risk of exposure to heat stress in dairy cattle in Uganda. Participants included agriculture and livestock officials, local non-governmental organizations (NGOs) and farmer associations, these stakeholder groups play a key role in working with vulnerable communities as they plan for climate change and/or respond to impacts of climate change. The main objectives were to (i) present results from objectives 1 and 2, and using focus group discussions, (ii) identify key activities affected by heat stress and their consequences in the dairy value chain, (iii) identify underlying factors to the consequences, and (iv) identify current and potential adaptation strategies and options.

This study adopted a climate change adaptation planning methodology by Mwongera et al. (2017), to assess how heat stress affects daily activities along the dairy value chain stages. The stages included supply of farm inputs, production at the farm, postharvest handling, and marketing products from the farm. Workshop participants were tasked with different activities i.e., characterization of the dairy value chain (*Appendix 1*), identification of key risks and consequences of heat stress on activities in the respective stages of the value chain (*Appendix 2*), and finally, assess ongoing and potential adaptation strategies for the established consequences (*Appendix 3*). The data collection tools were adapted from Mwongera et al. (2017). It is envisaged that data collected will feed in the development of adaptation plans for sharing and adoption by dairy farmers in the study area.

Data Analysis

Descriptive statistics were used to describe the data gathered during the workshop with stakeholders. First, all answers were first transcribed and rearranged. Main ideas for each question were noted and the general theme identified. Finally, findings were written down in Chapter 4, section 4.4.3.

CHAPTER 4: RESULTS AND DISCUSSION

4.4.1: Results and discussion for objective 1

4.4.1.1: Projected Average Relative Humidity (percent) and Average maximum temperature Changes

The projected average maximum temperature for RCPs 4.5 and 8.5 is summarized in Table 4.1 and Figure 4.1 (see also Appendix 1B for detailed figures for maximum temperature projections for RCPs 4.5 and 8.5 for the Periods 2021-2050 and 2071-2100 for all the districts in Uganda).

Table 4:1: Projected Average Maximum Temperature (°C) Changes based on RCPs 4.5 and 8.5 for the Periods 2021-2050 and 2071-2100 for Uganda

		RCP 4.5		**RCP 8.5**	
	Historical	**2021-2050**	**2071-2100**	**2021-2050**	**2071-2100**
Mean	30	30.2	31.1	30.4	32.9
Minimum	24.2	24.1	25.0	24.6	26.6
Maximum	33.8	34.2	35.2	34.5	36.0
Standard Deviation	2.1	2.2	2.2	2.2	2.3

RCP 4.5 is an optimistic scenario and has the lowest projected maximum temperature increases. The average maximum temperature increases in the 112 districts for periods 2021-2050 and 2071-2100 is 0.2°C and 1.1°C, respectively. Koboko, Maracha and Zombo districts are projected to have the highest increases at 0.4°C. Twenty-three districts will have no increase in maximum temperature. For the period 2021-2050, the forecasted maximum temperature in the Buyende district is expected to drop by 0.1°C. Yumbe, Koboko and Maracha districts are projected to have the highest increase at 1.4°C. Seventeen districts will have less than 1°C increase in maximum temperature for the period 2071-2100. In general, the findings are in line with IPCC (2014a), and earlier research conducted in the country (McSweeney et al., 2007).

RCP 8.5 is a pessimistic scenario and has the highest projected maximum temperature increases. The average maximum temperature increases in the 112 districts for periods 2021-2050 and 2071-2100 is 0.4°C and 2.9°C respectively. Arua, Lamwo, Bukwo, Zombo, Yumbe, Koboko and Maracha districts are projected to have the highest increases at 0.6°C. Thirteen districts will have less than 0.3°C increase in maximum temperature for the period 2021-2050. Kabale, Arua, Yumbe, Koboko and Maracha districts are projected to have the highest increase at 3.2°C. Buyende and Nakasongola districts will have less than 2.6°C increase in maximum temperature for the period 2071-2100.

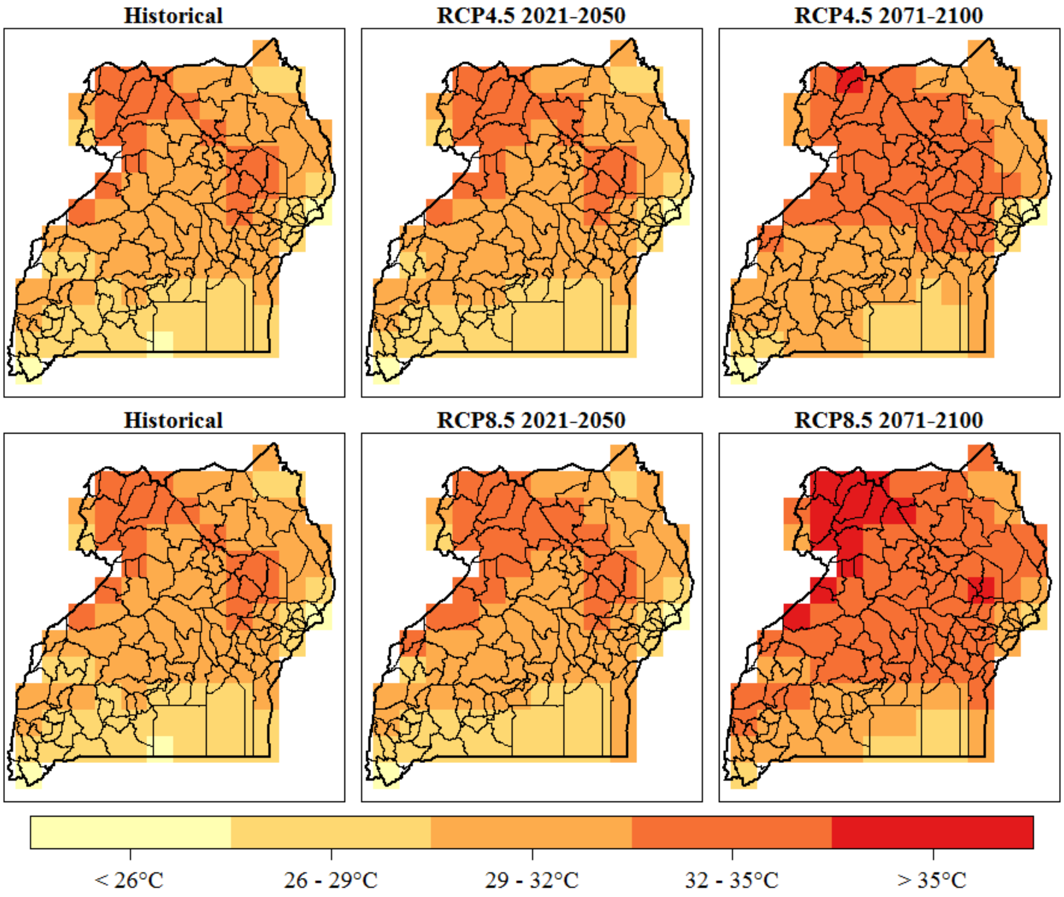

Figure 4.1: Average Maximum Temperature (°C) Based on RCPs 4.5 and 8.5 for the Historical and Future Periods (2021-2050 and 2071-2100) for Uganda

The projected average relative humidity for RCPs 4.5 and 8.5 is summarized in Table 4.2 and Figure 4.2 (see also Appendix 1A for detailed figures for relative humidity projections for RCPs 4.5 and 8.5 for the Periods 2021-2050 and 2071-2100 for districts in Uganda.

Table 4:2: Projected Average Relative Humidity (percent) Changes Based on RCPs 4.5 and 8.5 for the Periods 2021-2050 and 2071-2100 for Uganda

		RCP 4.5		**RCP 8.5**	
	Historical	**2021-2050**	**2071-2100**	**2021-2050**	**2071-2100**
Mean	56.5	58.5	58.6	58.4	59.0
Minimum	43.7	43.1	43.0	43.2	42.8
Maximum	72.1	76.5	77.2	76.5	78.8
Standard Deviation	7.6	8.7	8.9	8.7	9.4

RCP 4.5 is an optimistic scenario and has the lowest projected relative humidity increases. The average relative humidity increases in the 112 districts for periods 2021-2050 and 2071-2100 is 2.0 percent and 2.1 percent, respectively. Kayunga and Buyende districts are projected to have the highest increases at 4.4 percent while Nwoya is projected to have the lowest increases of 0.4 percent for period 2021-2050. Koboko, Yumbe, Maracha and Arua districts are projected to have a decrease in projected relative humidity for the period 2021-2050. For the period 2071-2100, Buyende district is expected to have the highest increase of 5.1 percent, while Nebbi and Moyo are expected to have the lowest increases of 0.2 percent. Koboko, Yumbe, Maracha and Arua districts are projected to have a decrease in projected relative humidity for the period 2071-2100.

RCP 8.5 is a pessimistic scenario and has the highest projected relative humidity increases. The average relative humidity increases in the 112 districts for periods 2021-2050 and 2071-2100 is 1.9 percent and 2.5 percent, respectively. For the period 2021-2050, Buyende district is expected to have the highest increase of 4.4 percent, while Zombo and Bukwo are expected to have the lowest increases of 0.1 percent. Koboko, Yumbe, Maracha and Arua districts are projected to have a decrease in projected relative humidity for the period 2021-2050. For the period 2071-2100, Buyende district is expected to have the highest increase of 6.7 percent, while Kanungu is expected to have the lowest increase of 0.1 percent. Yumbe, Koboko, Nebbi, Ntoroko, Rakai and Masaka districts are projected to have a decrease in projected relative humidity for the period 2071-2100.

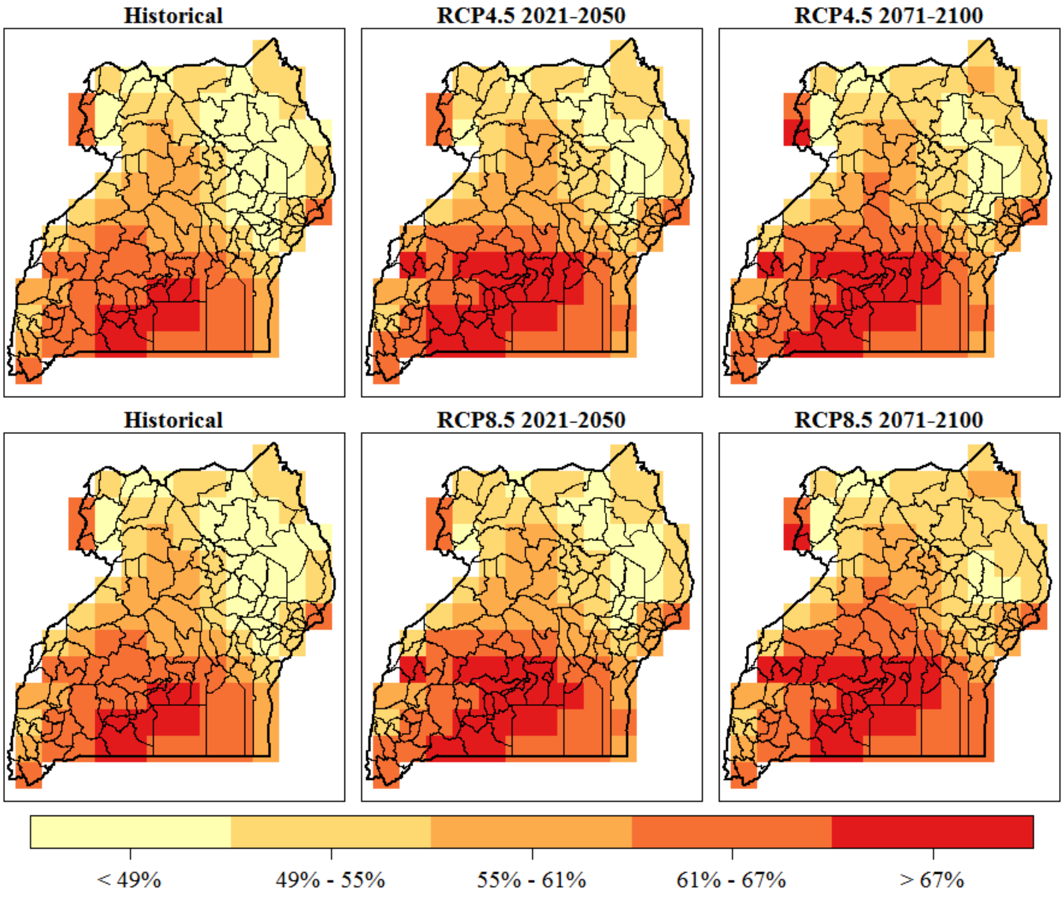

Figure 4.2: Average Relative Humidity (percent) in Uganda for Historical and Future Periods (2021-2050 and 2071-2100) based on RCPs 4.5 and 8.5

Figure 4.3 shows the long-term THI averages for the historical and future periods based on long-term averages in maximum temperature and relative humidity. RCP 4.5 has the lowest projected THI increases while RCP 8.5 has the highest projected THI increases. THI increase is mostly found in the northwestern parts of the country. In this region past studies have detected effects of climate change such as increased temperature (Egeru et al., 2019). However, adaption options have proven to be successful (Wichern et al., 2019).

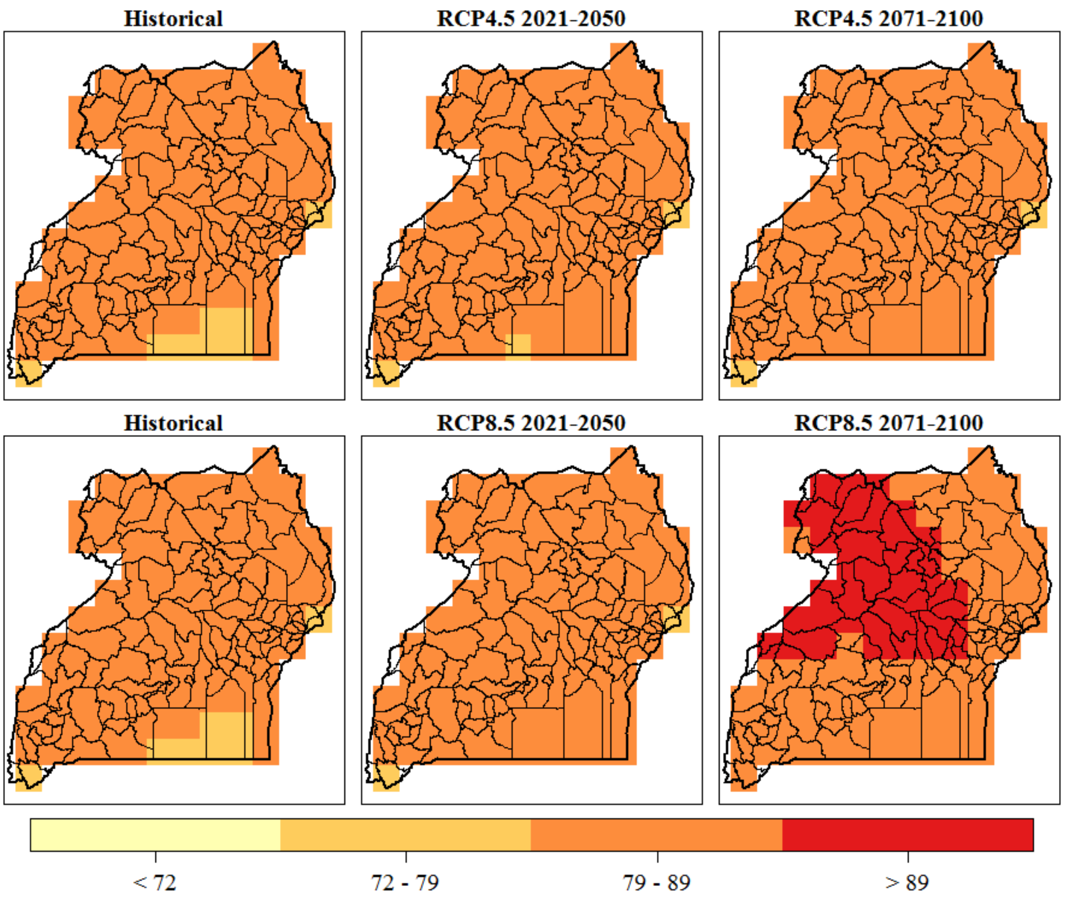

Figure 4.3: Long-term THI averages for the historical and future periods

4.4.1.2: Accuracy of ERA-Interim and Ensemble GCMs for simulating heat stress categories for dairy cattle

Figure 4.4 depicts how many times the daily THI categories simulated with ERA-Interim and ensemble GCMs datasets were the same with the one calculated by the observed climate values. As is apparent from this graph, during the historical period, both climate datasets were able to successfully reproduce the daily THI classifications (1981-2010). Based on the obtained results, no statistically significant differences (at the 95 percent confidence level) were noticed. Both climatic datasets were essentially identical in terms of simulations of THI categories for dairy cattle in Uganda, and they were in good agreement with the observed THI categories in synoptic stations (70 percent) when overlayed in annual time scale. As a result, based on ERA-Interim data, the results were presented and analyzed for the historical era (1981-2010), and under the RCP 4.5 and RCP 8.5 emission scenarios, anticipated changes in the future climate (2021-2050 and 2071-2100) were calculated using ensemble GCMs.

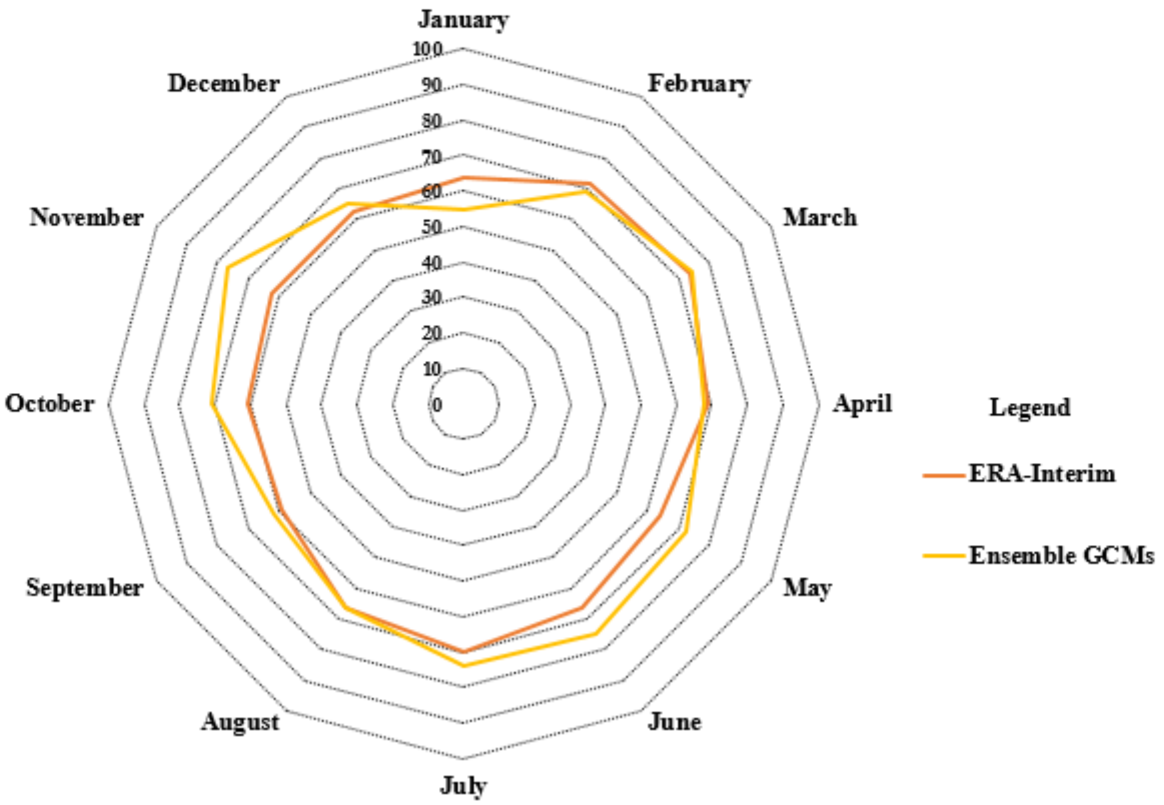

Figure 4.4: Spider chart showing agreement between the results of THI calculations based on two global datasets (ERA-Interim and multi model ensemble GCMs) and observational data for different months over Uganda

4.4.1.3: Ugandan Heat Stress Conditions in the Past

Table 4.3 summarizes the historical average occurrence of severe heat stress (1981-2010) and the expected average occurrence of severe heat stress for RCPs 4.5 and 8.5 (see also sections 4.4.1.3, 4.4.1.4, Figures 10, 11, 12, 13 and Appendix 1C for detailed figures for occurrence of severe heat stress projections for RCPs 4.5 and 8.5 for the Periods 2021-2050 and 2071-2100 for districts in Uganda.

Table 4:3: Projected Average Frequency (percent) of Severe Heat Stress Changes Based on RCP 4.5 and 8.5 for Periods 2021-2050 and 2071-2100 for Uganda

		RCP 4.5		**RCP 8.5**	
	Historical	**2021-2050**	**2071-2100**	**2021-2050**	**2071-2100**
Mean	2.3	0.8	5.0	1.5	30.5
Minimum	0	0	0	0	0

Maximum	17	17.3	50.4	25.3	82.4
Standard Dev	3.6	2.9	10.7	4.5	26.7

Figure 4.5 depicts the regional distribution of average heat stress frequencies for dairy cattle in Uganda over the historical period (1981-2010), with none, mild, moderate, and severe conditions. According to the figure, the frequency of the category "no heat stress" for dairy cattle, i.e., conditions in which the animal performs at its best in terms of productivity and reproduction, is roughly 6 percent (21 days per year) on average. Furthermore, mild heat stress was most prevalent in Uganda's western regions, with a frequency of roughly 20 percent (73 days per year) on average. In the western, middle, and eastern sections of the country, the frequency of moderate heat stress ranged from less than 2 percent (7 days per year) to more than 80 percent (290 days per year) in the northern and eastern regions of the country. The average frequency of moderate heat stress events was 64 percent across the country (233 days per year) while the average frequency of severe heat stress conditions for dairy cattle during the historical period was ~10% (37 days per year).

Specifically, between 1981 and 2010, the average frequency of severe conditions ranged from less than 2.5 percent (less than ~9 days per year) in the southern parts of Uganda while in the country's northwestern regions, this figure has risen to more than 20% (~73 days per year).

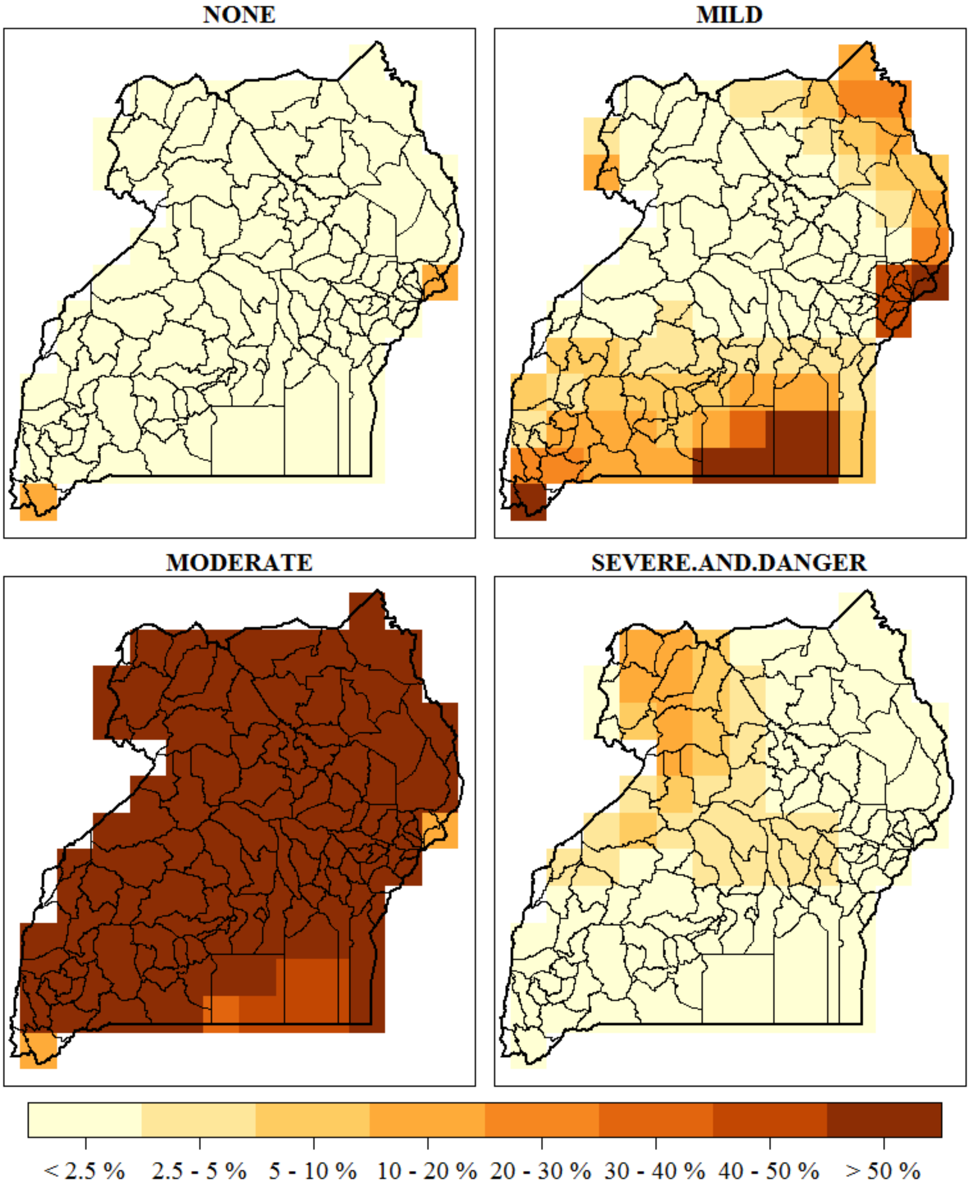

Figure 4.5: Frequency of various Thermal Humidity Index categories for dairy cattle during the historical period (1981-2010)

Figure 4.6 shows that during the historical period, the frequency of severe heat stress in dairy cattle increased significantly ($p<0.05$) in 38 percent of the country. Much of the large rise is concentrated in the country's northern and central regions.

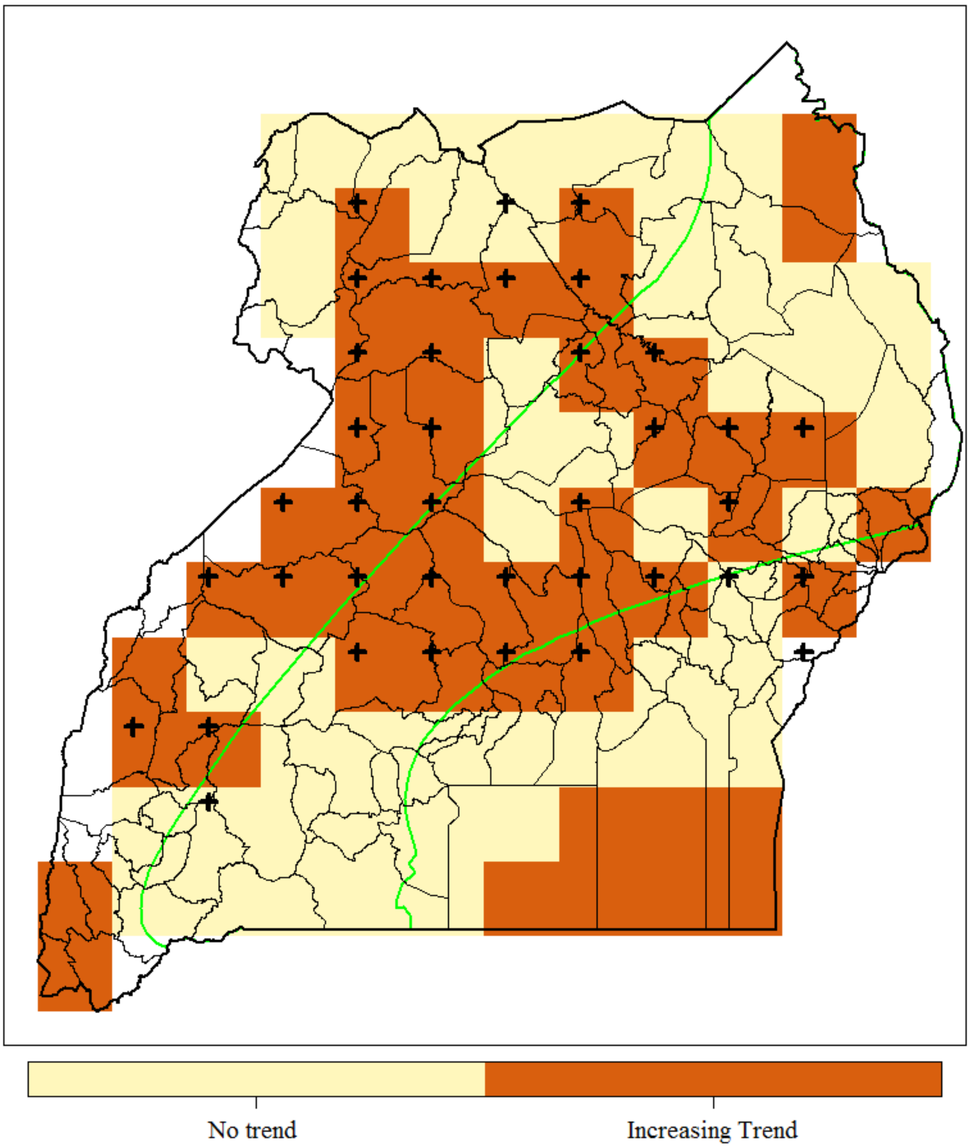

Figure 4.6: Trends in the frequency of Severe heat stress condition for dairy cattle during the historical period of 1981-2010 (Plus (+) indicates trend values significant at 95% confidence level). The cattle corridor is indicated as the region between the green borders

4.4.1.4: Future Heat Stress Condition (2021-2050 and 2071-2100)

The primary findings of a study employing multi-model ensemble GCMs to predict changes in heat stress conditions for dairy cattle in Uganda under RCP 4.5 and RCP 8.5 emission scenarios for two future periods (2021-2050 and 2071-2100) are presented in Table 4.4 and

Figures 4.7 and 4.8. In both illustrations, simulations under both RCP scenarios indicated that there would be a gradual shift towards more severe conditions in the study area.

Table 4:4: Average frequency (percent) of THI categories by 2021-2050 and 2071-2100 period under RCP 4.5 and RCP 8.5 scenarios

THI Category	**Historical Period**	**Future Periods**			
		RCP 4.5		**RCP 8.5**	
		2021-2050	**2071-2100**	**2021-2050**	**2071-2100**
None	6	3	2	3	1
Mild	20	18	14	17	8
Moderate	64	68	70	68	66
Severe	10	11	14	12	25

Under RCP 4.5, the frequency of severe heat stress would increase by 1 percent (four days per year) between 2021 and 2050, whereas under RCP 8.5, it would increase by 2 percent (seven days per year). In some regions like north-western parts of the country, dairy cattle would experience around ~200 days/year with severe heat stress condition more than the historical period. North-eastern parts of the country will remain the same with no severe heat stress conditions based on both RCPs for 2021-2050 period.

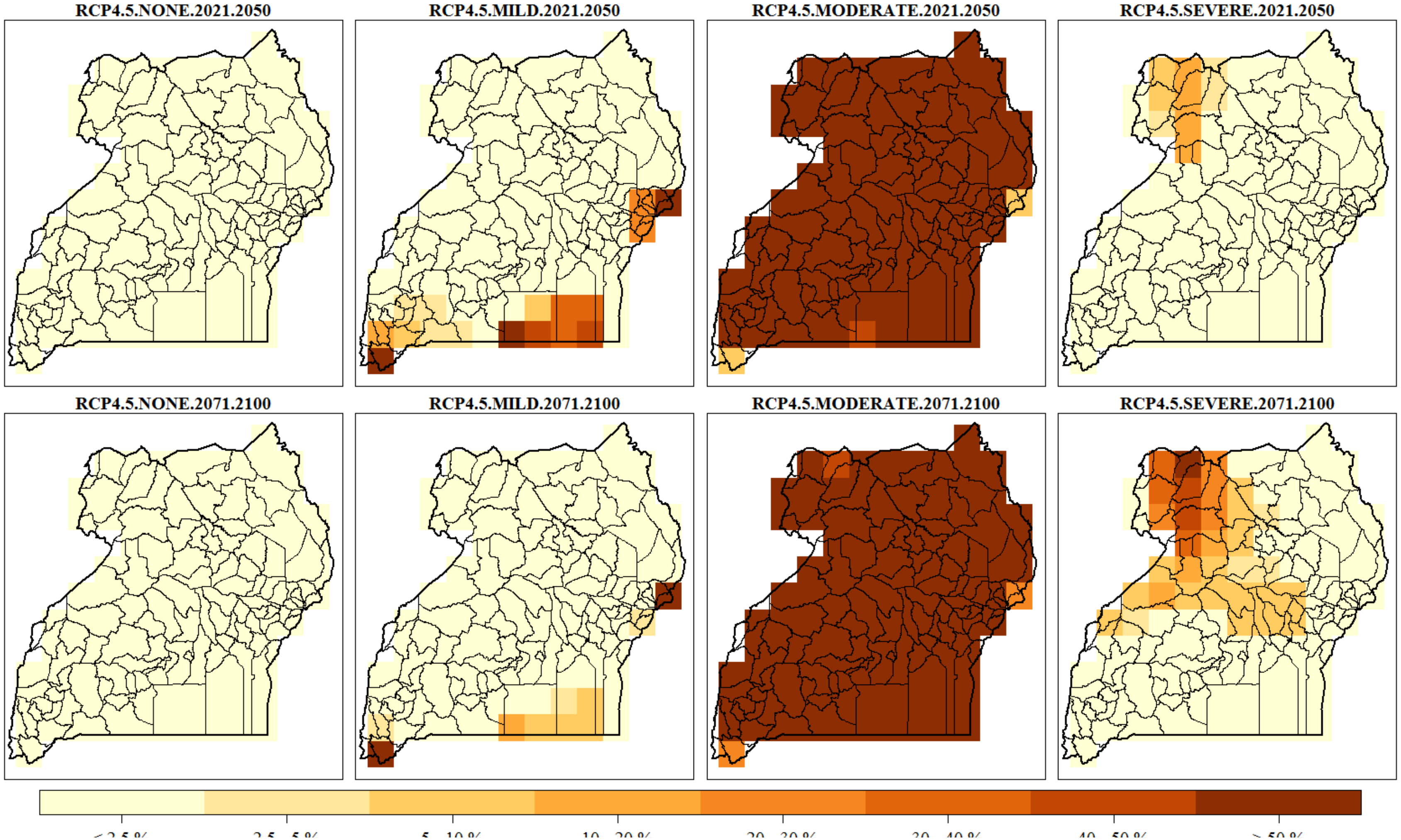

Figure 4.7: Frequency of different Thermal Humidity Index categories for dairy cattle by 2021-2050 and 2071-2100 periods under RCP 4.5 scenario

Under RCP 4.5, the occurrence of extreme heat stress would increase by 2 percent (7 days/year) throughout the 2071-2100 timeframe, whereas under RCP 8.5, it would increase by 15 percent (55 days/year). In some regions like north-western parts, dairy cattle would experience around ~200 days/year with severe heat stress condition more than the historical period. During the 2071-2100 timeframe, the frequency of severe heat stress would increase by 3 percent (10 days/year) in the north-eastern regions of the study area for both RCPs.

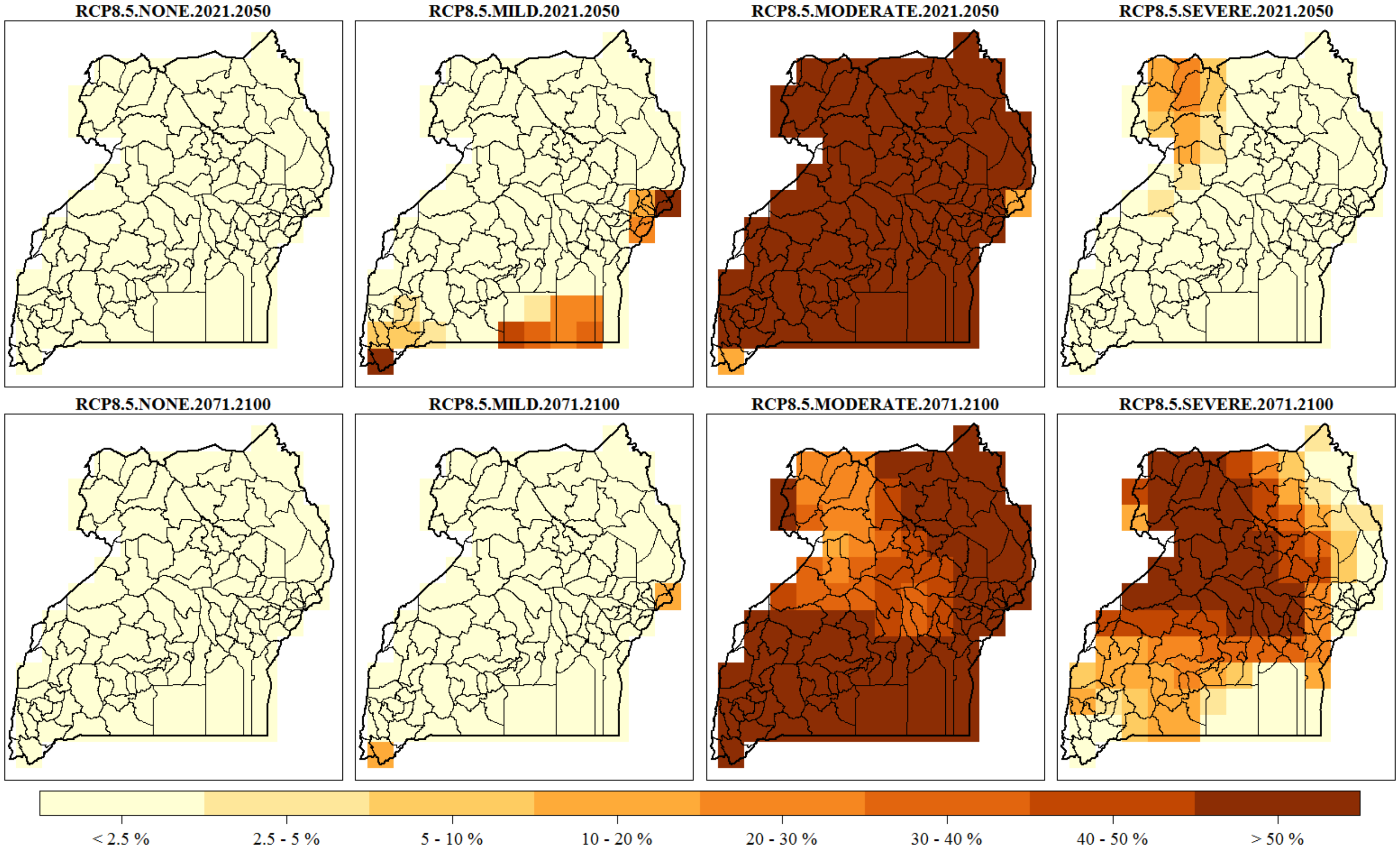

Figure 4.8: Frequency of Thermal Humidity Index categories for dairy cattle by 2021-2050 and 2071-2100 periods under RCP 8.5 scenario

4.4.2: Results and discussion for objective 2

4.4.2.1: Dairy cattle population at risk in Uganda

According to MAAIF/UBOS (2010), breeds including dairy, exotic, or crosses make up 47.8 percent of the cattle population. These are the breeds that will be mostly likely affected by heat stress. Based on the spatial analysis between overlaying the cattle and the heat stress maps, approximately 67,810 dairy cattle fall in areas with a mild THI while 3,449,970 falls in areas with a moderate THI. As seen in Figure 4.9, most of the country's largest livestock production is conducted in the central and southwestern regions, otherwise known as the cattle corridor (Area indicated as the region between the green borders stretching from Southwest to the Northeast), and parts of Nakaseke and Nasongola in central parts, which are dominated by pastoral rangelands with many semi-arid characteristics. In this region, there is a significant increase in severe heat stress events covering 38 percent of the country. Temperature has been projected to increase for both near future and mid-century periods in this region by previous studies (Nimusiima et al., 2014; Owoyesigire et al., 2016).

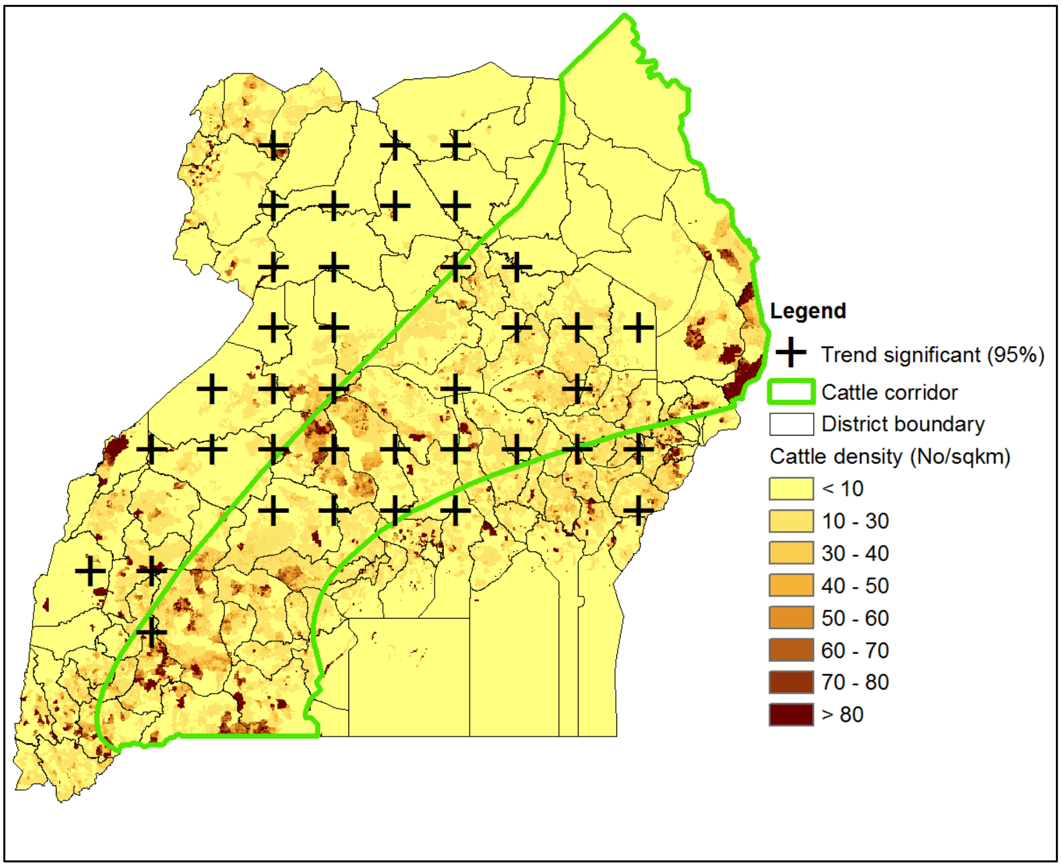

Figure 4.9: The population of dairy cattle in Uganda at risk of severe heat stress conditions (plus (+) indicates trend values that are significant at a 95% confidence level; see figure 10). The area between the green borders is the cattle corridor

4.4.2.2: Projected impact on dairy production

Figure 4.10 shows the percentage of dairy production where the frequency of moderate and severe heat stress is anticipated to vary significantly (at a 95 percent confidence level) by 2021-2050 and 2071-2100, respectively, under RCP 4.5 and RCP 8.5 scenarios.

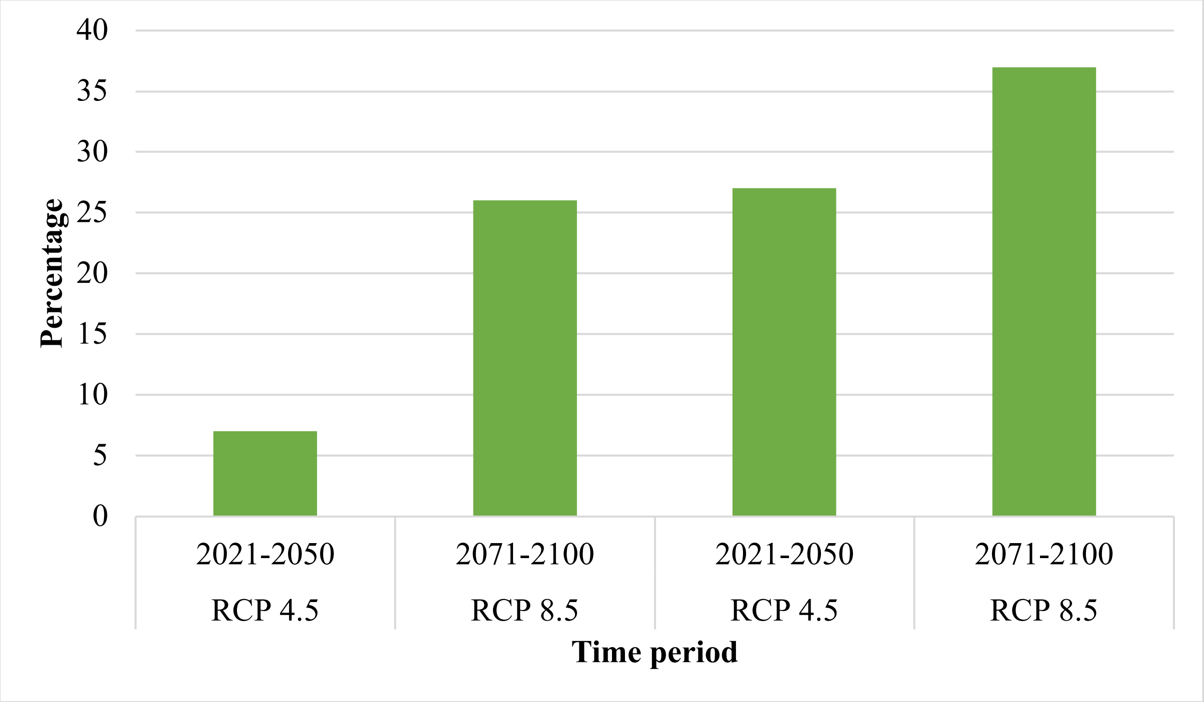

Figure 4.10: Percentage of Uganda's current milk output that will be severely hampered (at 95 percent confidence level) by increasing the frequency of Moderate and Severe Heat stress categories by 2021-2050 and 2071-2100 periods under RCPs 4.5 and 8.5

As presented in Figure 4.11, approximately ~7 percent (~175 000 000 litres), ~26 percent (~650 000 000 litres), ~27 percent (~675 000 000 litres) and ~37 percent (~925 000 000 litres) of the current milk production takes places where the frequency for both moderate and severe heat stress, is likely to become more common in the future by 2021-2050 and 2071-2100 under RCP 4.5 and RCP 8.5, respectively. This is quite substantial compared to the figures reported by UBOS (2019) for 2018.

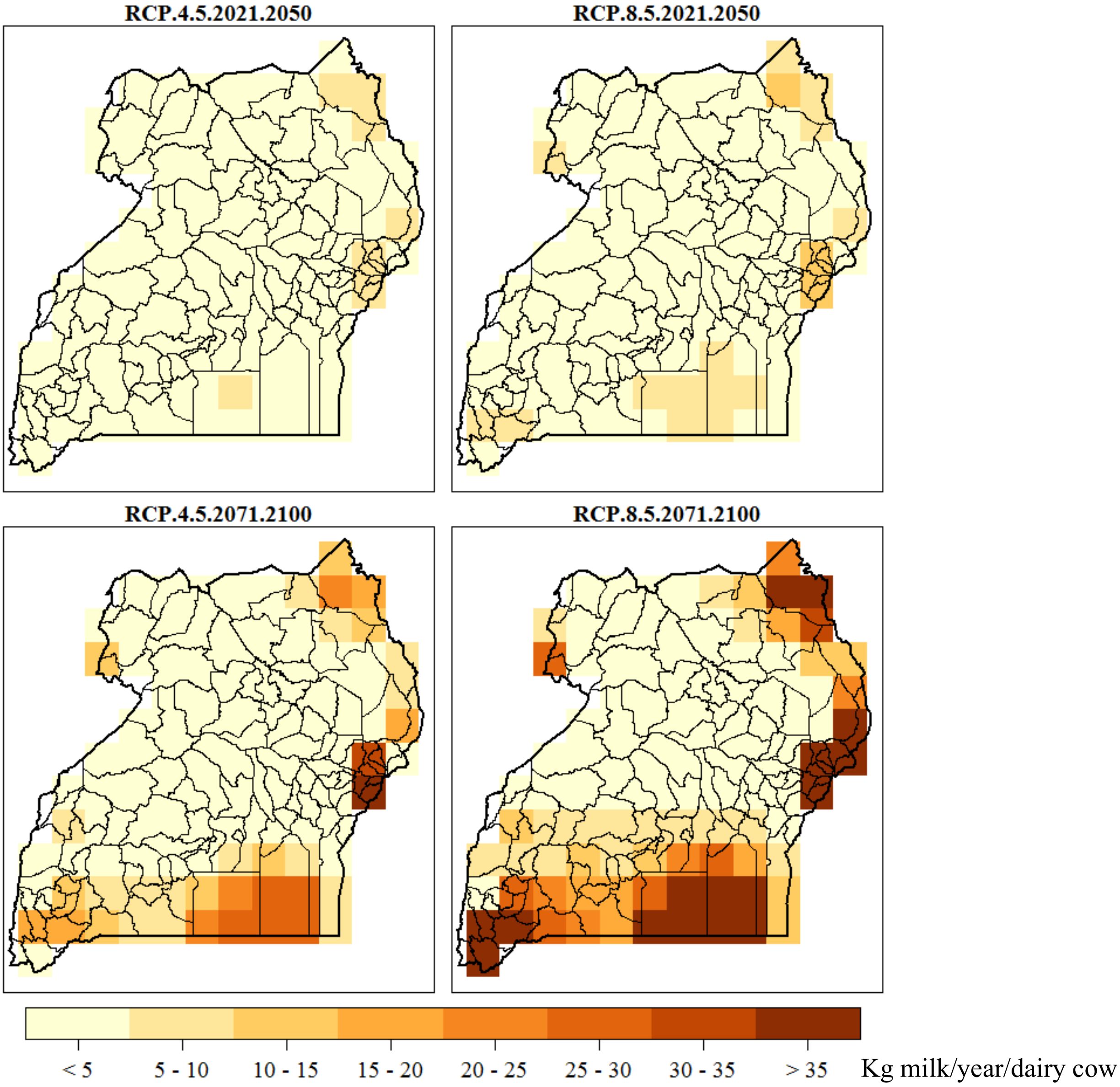

Figure 4.11: Milk production at risk of change in the frequency, intensity, and duration of moderate and severe heat stress under future climate conditions (2021-2050 and 2071-2100) under RCP 4.5 and 8.5 scenario; Units kg/milk/year/dairy cow

On average, the milk loss due to heat stress is estimated at 1.4 and 6.0 kg milk/year/dairy cow for 2021-2050 and 2071-2100 respectively based on RCP 4.5 and 2.3 and 15.6 kg milk/year/dairy cow for 2021-2050 and 2071-2100 respectively based on RCP 8.5. Although heat stress has been identified as one of the major affect dairy cattle (Thornton et al., 2015), there has not been studies in the country to assess the impact on production. In this study, an attempt is made to assess this. Figure 4.10 illustrates that the districts of Kaabong, Manafwa, Bududa, Sironko, and Kapchorwa are expected to have the most drastic shifts in milk output in the future. These are high cattle density regions as shown in section 3.3.3 where the number of cattle is above 200 per square kilometre. These districts are mainly medium to high elevation ranging from 1200 to 1800 metres above sea level with high points touching Mt Elgon National Park. In these areas, farmers practice mixed rainfed agriculture which makes them highly vulnerable to climate change (Bomuhangi et al., 2016). Appendix 2 provides a more extensive analysis of the influence on milk production at the district level of changes in the frequency, intensity, and duration of moderate and severe heat stress under future climate conditions (2021-2050 and 2071-2100) under the RCP 4.5 and 8.5 scenarios.

4.4.3: Results and discussion for objective 3

In Uganda, the dairy value chain employs approximately 37 percent of the population. The input supply and on-farm production stages are dominated by small-scale farmers. This reaffirms the use of smallholder dairy farming as a strategy for the country's economic transformation via commercialization (Balirwa & Waholi, 2019). On farm production stage is composed of eighty percent, fifteen percent, and five percent small-scale, medium-scale and large-scale actors, respectively. Women perform most of the operations such as milking and feeding, with the youth playing a medium part in the input and on-farm production stages. These results confirm what was documented by Sempiira et al. (2017), a study that called for an improvement in production processes to decrease the labour burden in women. Men are mostly in charge of obtaining feed and other supplies. Post-harvest stage is mainly composed of three players i.e., large-scale who do the bulking, small-scale who do the processing and medium scale who do the transportation. Milk processing, which is mostly composed of few large-scale processors, and dominated by small-scale wholesalers. Because of the limited activities, these stages employ fewer people than the other stages of the dairy value chain. Men are heavily involved at this stage, with the youth giving medium assistance. The output market is mainly composed of small-scale retailers. Eighty percent of the processed milk is sold while sixty seven percent is consumed locally through retailers. Men play a large role in marketing, with youth playing a medium one. The key activities in the dairy value chain are listed in Table 4.5.

Table 4:5: Characterization of the activities and the actors involved in the dairy value chain in Uganda

Stage	**Important activities**	**Service provider**
Input supply	Providing drugs	Input suppliers, agro dealers
	Forage production	Own production, Input suppliers and agro dealers
	Provision of breeding stock	Government, private entities
On-farm production	Feeding (Provision of feeds)	Farmers
	Milking	Farmers
	General management (Disease control, manure management, product quality, cow comfort)	Government and farmers
Post-harvest	Transporting	Farmer groups and traders
	Milk bulking	Individual farmers as well as cooperatives
	Processing (Small-scale, medium, and large)	Individual farmers as well as cooperatives
Output market	Retailing (Raw and processed milk)	Cooperatives, groups, and traders
	Wholesaling (Producers)	Cooperatives, groups, and traders
	Exporting (processors)	Cooperatives

Heat stress has a significant impact on dairy production. As seen in Table 4.6, the implications are felt at every stage of the value chain.

Table 4:6: The impact of heat stress on Uganda's dairy value chain activities

Stage	**Consequence**	**Severity**	**Who is impacted**
Input supply	Affects the storage of drugs, potency, and shelf life	Major	Men, youth, and women
	Reduced quantity and quality	Severe	Men, youth, and women
	Reduces the conception rate and feed intake	Severe	Men and women

On farm production	In availability of feeds and water as well as feed intake	Severe	Men, youth, and women
	Reduced production and milk quality	Severe	Men, youth, and women
	There is no cow comfort hence low productivity	Severe	Everyone is affected
Post-harvest	It reduces on the quality of the milk and expensive cost of transporting in cooling tanks	Severe	Men and youth
	Increased cost of cooling, Reduction in milk volumes, Reduced income	Severe	Men, youth, and women
	Poor quality, less quantity, Increased cost of production, Increased bacterial load	Severe	Men
Output market	Milk quality is poor, Consumers will not buy the product	Severe	Men, youth, and women
	Poor milk quality, reduced shelf life, High rejections and returns	Severe	Men, youth, and women
	Milk will not meet the quality standards of the exporting nations, No exporting again/ blacklist	Severe	Government, men, youth, and women

To anticipate or respond to heat stress owing to institutional, political, economic, sociocultural, geographical, or biophysical variables is one of the key underlying elements for the effects described above. This has been documented by previous studies (Balikoowa et al., 2019; Cooper & Wheeler, 2017; Wichern et al., 2019). In a recent study in Kenya with no different systems, lack of available information was identified as a constraint to adoption of climate smart technologies for improved dairy production systems (Owino et al., 2020; Watende, 2016). Farmers' lack of critical heat stress adaptation knowledge and practical skills is exacerbated by insufficient farmer extension services (Ampaire et al., 2017b). Poverty exacerbates the problems by limiting farmers' access to resources. Inequalities, social exclusion, and discrimination based on gender, age, or socioeconomic position are exacerbated by community values, attitudes, beliefs, and practices regarding gender roles, asset ownership, and value chain involvement. Although women are very much involved in on-farm production of milk, men make most of the decisions and control the resources. Heat stress is dispersed spatially throughout the country, and the location of agricultural areas exposes certain farmers to it more than others. In the dairy value chain, current adaptation options include those aimed at enhancing production, such as crossbreeding of indigenous breeds e.g., Ankole with improved breeds. However, previous research has shown increased commercialization of the smallholder dairy sector is threatening the Ankole cattle (Wurzinger et al., 2006). The proposed adaption options are more comprehensive, with the majority focusing on all stages of the value chain. These activities are listed in Table 4.7.

Table 4:7: Ongoing and prospective responses to heat stress in Uganda's dairy value chain activities

Stage	**Ongoing**	**Potential**
Input supply	Storage of drugs in ceilings	Enforcing quality standards of drugs
	Promotion of conservation feeding	Use of improved varieties of forages e.g., Brachiaria species
	Cross breeding of breeds e.g., Friesians to jerseys for more adaptability	Adoption of better suited breeds
On-farm production	Promotion of resilient pastures	Introduction of new pasture species to improve palatability
	Use of energy efficient coolers to preserve the milk	Introduction of milk coolers on the farm for instant cooling
	Use of appropriate sheds which are easy to clean and well aerated	Research and innovation on appropriate housing
Post-harvest	Use of milk tankers that are insulated to transport milk during the day	Use of refrigerators boxes to transport milk from the farm to the bulking center
	Use of chilling facilities like coolers	Increase on the energy efficiency of cooling systems
	Use of milk testing equipment at farm level i.e., Farmer training through extension services	Investment in the cold chain technology up to farm level
Output market	Training in proper milk handling practices	Provision of mobile chillers
	Use of cold rooms and refrigerated trucks	Emphasize enforcement for standards
	Working under established standards	Research on low-cost energy efficient systems

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1: Conclusion

The aim of this study was to map potential risk of exposure to heat stress for dairy cattle under current (1981-2010) and future (2021-2050 and 2071-2100) projected climatic conditions in Uganda using THI.

Between 1981 and 2010, most areas, particularly in the central parts of the country, had an increase in moderate to severe heat stress in dairy cattle, according to this study. Under future climate circumstances, the frequency of severe heat stress conditions is predicted to rise dramatically, particularly in the country's northwestern regions, which will experience more than 200 days/year with severe heat stress condition more than the historical period. Most of the area affected is in the Uganda's cattle corridor - a zone stretching from dominated by pastoral rangelands. The increasing frequency of severe heat stress in this area due to climate change is a new challenge for milk production in the country. This is concerning because the demand for livestock products is expected to skyrocket in the future (Rojas-Downing et al., 2017), and there is an expected significant increase in population (Boke-Olén et al., 2017).

Climate change is likely to increase average temperatures by up to 3 to 5 ºC by 2100 (IPCC, 2018). Such rates of increase at the local level will have negative consequences. For example, most of Uganda's largest livestock production area falls in the central and southwestern regions, an area that falls in the cattle corridor. It is in these regions where there is a significant increase in severe heat stress events covering 38 percent of the country. Furthermore, more than 20 percent of present milk production occurs in areas where moderate and severe heat stress is predicted to become more common in the future. The losses are estimated to be on average 14 and 33 tons of milk based on business as usual (RCP 4.5) and worst case (RCP 8.5) scenario, respectively.

The dairy production systems in Uganda are evolving to become more business-oriented systems. However, to stay sustainable, climate change adaptation of these systems should be a top priority. Based on the findings of this study, it indicates that most regions of the country will face a gradual transition toward more severe circumstances in the future. The anticipated changes in heat stress events in Uganda described in this study points to significant implications for the overall dairy cattle production system as such this study calls for a multi-stakeholder engagement in a bid to ensure that Uganda sets the pace in supporting future heat stress management in the dairy sector.

5.2: Recommendation

Future heat stress management strategies in the dairy sector will require informed investment from the donor community to accelerate climate-smart technologies targeted at making present dairy production systems more resilient. Promotion of adaptation technologies like heat stress tolerant dairy breeds is key. The government which is the custodian of livestock policies should realign related policies to ensure they support heat stress management with support from a range of stakeholders for example in science, the Green Climate Fund (GCF), public and private sectors, non-governmental organizations, and civil society.

Heat-stress adaptation should now be made a priority in the country and mainstreamed into dairy sector development initiatives. Knowledge regarding effective strategies for dealing, adapting, or minimizing it should be disseminated at farm level. More studies are needed to understand the factors influencing the adoption of dairy heat stress adaptation amongst smallholder farmers. Smallholder dairy farmers should be provided with capacity building to be able to quickly identify vulnerable or heat-stressed dairy animals. This can be made possible through current extension systems for heat stress prevention and mitigation. Most importantly, women should be empowered with this information since they are the most actors at the production value chain stage level.

Uganda's dairy production systems are becoming more vulnerable because of climate change and challenges decision-makers to decide what the most effective adaptation decisions. This research demonstrates how geographic information systems can be a useful tool for assessing present and future trends in heat stress for livestock, as well as identifying areas where specific livestock may be at danger of heat stress. This thesis contributes to the challenge faced by decision-makers in the livestock industry of developing evidence-based policy and targeted resource allocation so that farmers can be guided and aided in preparing for heat stress.

REFERENCES

Ampaire, E. L., Jassogne, L., Providence, H., Acosta, M., Twyman, J., Winowiecki, L., & van Asten, P. (2017a). Institutional challenges to climate change adaptation: A case study on policy action gaps in Uganda. *Environmental Science & Policy*, *75*, 81–90. https://doi.org/10.1016/J.ENVSCI.2017.05.013

Ampaire, E. L., Jassogne, L., Providence, H., Acosta, M., Twyman, J., Winowiecki, L., & van Asten, P. (2017b). Institutional challenges to climate change adaptation: A case study on policy action gaps in Uganda. *Environmental Science & Policy*, *75*, 81–90. https://doi.org/10.1016/j.envsci.2017.05.013

Anri, A. (2012). *Manual for Mastitis Control in Developing Countries*. 37–56.

Arinaitwe, B. N., & Baluka, S. A. (2019). Do extension services influence milk production among dairy farmers' cooperatives? *International Journal of Agricultural Extension and Rural Development Studies*, *6*(3), 1–10.

Atube, F., Malinga, G. M., Nyeko, M., Okello, D. M., Alarakol, S. P., & Okello-Uma, I. (2021). Determinants of smallholder farmers' adaptation strategies to the effects of climate change: Evidence from northern Uganda. *Agriculture & Food Security*, *10*(1), 6. https://doi.org/10.1186/s40066-020-00279-1

Bakyayita, G. K., Norrström, A. C., & Kulabako, R. N. (2019). Assessment of Levels, Speciation, and Toxicity of Trace Metal Contaminants in Selected Shallow Groundwater Sources, Surface Runoff, Wastewater, and Surface Water from Designated Streams in Lake Victoria Basin, Uganda. *Journal of Environmental and Public Health*, *2019*. https://doi.org/10.1155/2019/6734017

Balikoowa, K., Nabanoga, G., Tumusiime, D. M., & Mbogga, M. S. (2019). Gender differentiated vulnerability to climate change in Eastern Uganda. *Climate and Development*, *11*(10), 839–849. https://doi.org/10.1080/17565529.2019.1580555

Balikowa, D. (2011). *Dairy development in Uganda: A review of Uganda's dairy industry*.

Balirwa, E. K., & Waholi, E. (2019). Analysis of Market Participation Behavior Among Smallholder Dairy Farmers in Uganda. *Journal of Agricultural Science*, *11*(3), 109. https://doi.org/10.5539/jas.v11n3p109

Barrada, M. S. (1957). *Responses of dairy cattle to hot environments with special emphasis on respiratory reactions*.

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., Roelandt, C., Seierstad, I. A., Hoose, C., & Kristjánsson, J. E. (2013). The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate. *Geoscientific Model Development*, *6*(3), 687–720. https://doi.org/10.5194/gmd-6-687-2013

Berman, A., Horovitz, T., Kaim, M., & Gacitua, H. (2016). A comparison of THI indices leads to a sensible heat-based heat stress index for shaded cattle that aligns temperature and humidity stress. *International Journal of Biometeorology*, *60*(10), 1453–1462. https://doi.org/10.1007/s00484-016-1136-9

Bianca, W. (1962). Relative Importance of Dry- and Wet-Bulb Temperatures in Causing Heat Stress in Cattle. *Nature*, *195*(4838), 251–252. https://doi.org/10.1038/195251a0

Bishop-Williams, K. E., Berke, O., Pearl, D. L., & Kelton, D. F. (2016). Mapping rural community and dairy cow heat stress in Southern Ontario: A common geographic pattern from 2010 to 2012. *Archives of Environmental & Occupational Health*, *71*(4), 199–207. https://doi.org/10.1080/19338244.2015.1058235

Bohmanova, J., Misztal, I., & Cole, J. B. (2007). Temperature-humidity indices as indicators of milk production losses due to heat stress. *Journal of Dairy Science*, *90*(4), 1947–1956. https://doi.org/10.3168/jds.2006-513

Boke-Olén, N., Abdi, A. M., Hall, O., & Lehsten, V. (2017). High-resolution African population projections from radiative forcing and socio-economic models, 2000 to 2100. *Scientific Data*, *4*(1), 1–9. https://doi.org/10.1038/sdata.2016.130

Bomuhangi, A., Nabanoga, G., Namaalwa, J. J., Jacobson, M. G., & Abwoli, B. (2016). Local communities' perceptions of climate variability in the Mt. Elgon region, eastern Uganda. *Cogent Environmental Science*, *2*(1), 1168276. https://doi.org/10.1080/23311843.2016.1168276

Botha, C. J., & Penrith, M.-L. (2008). Poisonous plants of veterinary and human importance in southern Africa. *Journal of Ethnopharmacology*, *119*(3), 549–558. https://doi.org/10.1016/j.jep.2008.07.022

Byaruhanga, J., Tayebwa, D. S., Eneku, W., Afayoa, M., Mutebi, F., Ndyanabo, S., Kakooza, S., Okwee-Acai, J., Tweyongyere, R., Wampande, E. M., & Vudriko, P. (2017). Retrospective study on cattle and poultry diseases in Uganda. *International Journal of Veterinary Science and Medicine*, *5*(2), 168–174. https://doi.org/10.1016/j.ijvsm.2017.07.001

Carabaño, M. J., Ramón, M., Menéndez-Buxadera, A., Molina, A., & Díaz, C. (2019). Selecting for heat tolerance. *Animal Frontiers*, *9*(1), 62–68. https://doi.org/10.1093/af/vfy033

Cardoso, R. M., Soares, P. M. M., Lima, D. C. A., & Miranda, P. M. A. (2019). Mean and extreme temperatures in a warming climate: EURO CORDEX and WRF regional climate high-resolution projections for Portugal. *Climate Dynamics*, *52*(1), 129–157. https://doi.org/10.1007/s00382-018-4124-4

Cargill, B. F., & Stewart, R. E. (1966). Effect of Humidity on Total Heat and Total Vapor Dissipation of Holstein Cows. *Transactions of the ASAE*, *9*(5), 0702–0706. https://doi.org/10.13031/2013.40077

Chylek, P., Li, J., Dubey, M. K., Wang, M., & Lesins, G. (2011). Canadian Earth System Model CanESM2 Observed and model simulated 20th century Arctic temperature variability: Canadian Earth System Model CanESM2 Canadian Earth System Model CanESM2. *Atmos. Chem. Phys. Discuss*, *11*, 22893–22907. https://doi.org/10.5194/acpd-11-22893-2011

Clark, E. L., Archibald, A. L., Daetwyler, H. D., Groenen, M. A. M., Harrison, P. W., Houston, R. D., Kühn, C., Lien, S., Macqueen, D. J., Reecy, J. M., Robledo, D., Watson, M., Tuggle, C. K., & Giuffra, E. (2020). From FAANG to fork: Application of highly annotated genomes to improve farmed animal production. *Genome Biology*, *21*(1), 285. https://doi.org/10.1186/s13059-020-02197-8

Collier, M. A., Jeffrey, S. J., Rotstayn, L. D., Wong, K. H., Dravitzki, S. M., Moeseneder, C., Hamalainen, C., Syktus, J. I., Suppiah, R., Antony, J., Zein, A. . El., & Atif, M. (2011). *The CSIRO-Mk3.6.0 Atmosphere-Ocean GCM: participation in CMIP5 and data publication*. 12–16.

Cooke, R. F., Cardoso, R. C., Cerri, R. L. A., Lamb, G. C., Pohler, K. G., Riley, D. G., & Vasconcelos, J. L. M. (2020). Cattle adapted to tropical and subtropical environments: Genetic and reproductive considerations. *Journal of Animal Science*, *98*(2). https://doi.org/10.1093/jas/skaa015

Cooper, S. J., & Wheeler, T. (2017). Rural household vulnerability to climate risk in Uganda. *Regional Environmental Change*, *17*(3), 649–663. https://doi.org/10.1007/s10113-016-1049-5

Das, R., Sailo, L., Verma, N., Bharti, P., Saikia, J., Imtiwati, & Kumar, R. (2016). Impact of heat stress on health and performance of dairy animals: A review. *Veterinary World*, *9*(3), 260–268. https://doi.org/10.14202/vetworld.2016.260-268

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., … Vitart, F. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828

Dufresne, J.-L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., … Vuichard, N. (2013). Climate change projections using the IPSL-CM5 Earth System Model: From CMIP3 to CMIP5. *Climate Dynamics*, *40*(9–10), 2123–2165. https://doi.org/10.1007/s00382-012-1636-1

Dunne, J. P., John, J. G., Shevliakova, E., Stouffer, R. J., Krasting, J. P., Malyshev, S. L., Milly, P. C. D., Sentman, L. T., Adcroft, A. J., Cooke, W., Dunne, K. A., Griffies, S. M., Hallberg, R. W., Harrison, M. J., Levy, H., Wittenberg, A. T., Phillips, P. J., & Zadeh, N. (2013). GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models. Part II: Carbon System Formulation and Baseline Simulation Characteristics*. *Journal of Climate*, *26*(7), 2247–2267. https://doi.org/10.1175/JCLI-D-12-00150.1

Egeru, A., Barasa, B., Nampijja, J., Siya, A., Makooma, M. T., & Majaliwa, M. G. J. (2019). Past, Present and Future Climate Trends Under Varied Representative Concentration Pathways for a Sub-Humid Region in Uganda. *Climate*, *7*(3), 35. https://doi.org/10.3390/cli7030035

Eisler, M. C., Magona, J. W., Jonsson, N. N., & Revie, C. W. (2007). A low cost decision support tool for the diagnosis of endemic bovine infectious diseases in the mixed crop-livestock production system of sub-Saharan Africa. *Epidemiology and Infection*, *135*(1), 67–75. https://doi.org/10.1017/S0950268806006571

Ekou, J. (2014). Dairy production and marketing in Uganda: Current status, constraints and way forward. *African Journal of Agricultural Research*, *9*(10), 881–888. https://doi.org/10.5897/AJAR2013.8470

Fabris, T. F., Laporta, J., Skibiel, A. L., Corra, F. N., Senn, B. D., Wohlgemuth, S. E., & Dahl, G. E. (2019). Effect of heat stress during early, late, and entire dry period on dairy cattle. *Journal of Dairy Science*, *102*(6), 5647–5656. https://doi.org/10.3168/jds.2018-15721

FAO. (2009). *The State of Food and Agriculture 2009*.

FAO. (2018). *Dairy Market Overview: Overview of global dairy market developments in 2018*.

Fodor, N., Foskolos, A., Topp, C. F. E., Moorby, J. M., Pásztor, L., & Foyer, C. H. (2018). Spatially explicit estimation of heat stress-related impacts of climate change on the milk production of dairy cows in the United Kingdom. *PLOS ONE*, *13*(5), e0197076–e0197076. https://doi.org/10.1371/journal.pone.0197076

Garner, J. B., Douglas, M., Williams, S. R. O., Wales, W. J., Marett, L. C., DiGiacomo, K., Leury, B. J., & Hayes, B. J. (2017). Responses of dairy cows to short-term heat stress in controlled-climate chambers. *Animal Production Science*, *57*(7), 1233–1233. https://doi.org/10.1071/AN16472

Gauly, M., & Ammer, S. (2020). Review: Challenges for dairy cow production systems arising from climate changes. *Animal*, *14*(S1), S196–S203. https://doi.org/10.1017/S1751731119003239

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., & Tempio, G. (2013). *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities*.

Gilbert, M., Nicolas, G., Cinardi, G., Van Boeckel, T. P., Vanwambeke, S. O., Wint, G. R. W., & Robinson, T. P. (2018). Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Scientific Data 2018 5:1*, *5*(1), 1–11. https://doi.org/10.1038/sdata.2018.227

Giorgetta, M. A., Jungclaus, J., Reick, C. H., Legutke, S., Bader, J., Böttinger, M., Brovkin, V., Crueger, T., Esch, M., Fieg, K., Glushak, K., Gayler, V., Haak, H., Hollweg, H.-D., Ilyina, T., Kinne, S., Kornblueh, L., Matei, D., Mauritsen, T., … Stevens, B. (2013). Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5. *Journal of Advances in Modeling Earth Systems*, *5*(3), 572–597. https://doi.org/10.1002/jame.20038

Grimaud, P., Faye, B., Mugarura, L., Muhoozi, E., & Bellinguez, A. (2004). Identification of research activities for the dairy sector development in Uganda: Systemic and participatory approaches. *Uganda Journal of Agricultural Sciences*, *9*, 879–884.

Gunn, K. M., Holly, M. A., Veith, T. L., Buda, A. R., Prasad, R., Rotz, C. A., Soder, K. J., & Stoner, A. M. K. (2019). Projected heat stress challenges and abatement opportunities for U.S. milk production. *PLOS ONE*, *14*(3), e0214665–e0214665. https://doi.org/10.1371/journal.pone.0214665

Hahn, G. L. (1997). Dynamic responses of cattle to thermal heat loads. *Journal of Animal Science*, *77*(suppl_2), 10–10. https://doi.org/10.2527/1997.77suppl_210x

Hahn, G. L., Parkhurst, A., & Gaughan, J. (1997). Cattle respiration rate as a function of ambient temperature. *Trans. ASAE*, *40*(6), 97–121.

Hazeleger, W., Wang, X., Severijns, C., Bintanja, R., Sterl, A., Wyser, K., Semmler, T., Yang, S., van den Hurk, B., van Noije, T., van der Linden, E., van der Wiel, K., Ştefãnescu, S., Bintanja, R., Sterl, A., Wyser, K., Semmler, T., Yang, S., van den Hurk, B., … van der Wiel, K. (2011). EC-Earth V2.2: Description and validation of a new seamless earth system prediction model. *Climate Dynamics*, *39*(11), 2611–2629. https://doi.org/10.1007/s00382-011-1228-5

Hempel, S., Menz, C., Pinto, S., Galán, E., Janke, D., Estellés, F., Müschner-Siemens, T., Wang, X., Heinicke, J., Zhang, G., Amon, B., Del Prado, A., & Amon, T. (2019). Heat stress risk in European dairy cattle husbandry under different climate change scenarios-uncertainties and potential impacts. *Earth System Dynamics*, *10*(4), 859–884. https://doi.org/10.5194/esd-10-859-2019

Hernández-Castellano, L. E., Nally, J. E., Lindahl, J., Wanapat, M., Alhidary, I. A., Fangueiro, D., Grace, D., Ratto, M., Bambou, J. C., & de Almeida, A. M. (2019). Dairy science and health in the tropics: Challenges and opportunities for the next decades. *Tropical Animal Health and Production*, *51*(5), 1009–1017. https://doi.org/10.1007/s11250-019-01866-6

Herrero, M., Thornton, P. K., Notenbaert, A., Msangi, S., Wood, S., Kruska, R., Dixon, J., Bossio, D., Steeg, J. van de, Freeman, H. A., Li, X., & P. ParthasarathyRao. (2012). *Drivers of Change in Crop–Livestock Systems and Their Potential Impacts on Agro-Ecosystems Services and Human Wellbeing to 2030: A Study Commissioned by the CGIAR Systemwide Livestock Programme International Livestock Research Institute*.

Hijmans, R. J. (2017). *Geographic Data Analysis and Modeling [R package raster version 2.6-7]*. Comprehensive R Archive Network (CRAN). https://cran.r-project.org/web/packages/raster/index.html

ILRI. (2007). *Dairy Farming in Uganda: Production Efficiency and Soil Nutrients under Different Farming Systems*.

ILRI. (2019). *Meat: The Future series Options for the Livestock Sector in Developing and Emerging Economies to 2030 and Beyond* (p. 28). World Economic Forum.

Ilukor, J., Birner, R., Rwamigisa, P. B., & Nantima, N. (2015). The provision of veterinary services: Who are the influential actors and what are the governance challenges? A case study of Uganda. *Experimental Agriculture*, *51*(3), 408–434. https://doi.org/10.1017/S0014479714000398

IPCC. (2014a). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White, Eds.; p. 688). Cambridge University Press.

IPCC. (2014b). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (R. K. Pachauri & L. A. Meyer, Eds.; pp. 151–151). Intergovernmental Panel on Climate Change.

IPCC. (2018). *Global warming of 1.5°C An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,* (V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield, Eds.). www.environmentalgraphiti.org

Jiang, B., Bamutaze, Y., & Pilesjö, P. (2014). Climate change and land degradation in Africa: A case study in the Mount Elgon region, Uganda. *Geo-Spatial Information Science*, *17*(1), 39–53. https://doi.org/10.1080/10095020.2014.889271

Jones, C. D., Hughes, J. K., Bellouin, N., Hardiman, S. C., Jones, G. S., Knight, J., Liddicoat, S., O'connor, F. M., Andres, R. J., Bell, C., Boo, K.-O., Bozzo, A., Butchart, N., Cadule, P., Corbin, K. D., Doutriaux-Boucher, M., Friedlingstein, P., Gornall, J., Gray, L., … Zerroukat, M. (2011). The HadGEM2-ES implementation of CMIP5 centennial simulations. *Geosci. Model Dev*, *4*, 543–570. https://doi.org/10.5194/gmd-4-543-2011

Kabunga, N. S., Ghosh, S., & Webb, P. (2017). Does ownership of improved dairy cow breeds improve child nutrition? A pathway analysis for Uganda. *PLOS ONE*, *12*(11), e0187816–e0187816. https://doi.org/10.1371/journal.pone.0187816

Kadzere, C. T. T., Murphy, M. R. R., Silanikove, N., & Maltz, E. (2002). Heat stress in lactating dairy cows: A review. *Livestock Production Science*, *77*(1), 59–91. https://doi.org/10.1016/S0301-6226(01)00330-X

Kaoga, J., Olago, D., George, O., Gilbert, O., & Joshua, O. (2021). Long-term spatial-temporal temperature characteristics of a pastoral ecosystem in Kajiado County, Kenya. *African Journal of Agricultural Research*, *17*, 896–906. https://doi.org/10.5897/AJAR2021.15544

Kasirye, N. F. M. (2003). *Milk and Dairy Products, Post-harvest Losses and Food Safety in Sub-Saharan Africa and the Near East. FAO Prevention of Food Losses Programme* (pp. 51–51).

Kelly CF, B. T. (1971). *Bioclimatic factors and their measurements. In: A guide to environmental research in animals* (pp. 77–77).

Kiggundu, N., Ddungu, S. P., Wanyama, J., Cherotich, S., Mpairwe, D., Zziwa, E., Mutebi, F., & Falcucci, A. (2019). Greenhouse gas emissions from Uganda's cattle corridor farming systems. *Agricultural Systems*, *176*, 102649–102649. https://doi.org/10.1016/j.agsy.2019.102649

Kim, E.-S., & Rothschild, M. F. (2014). Genomic adaptation of admixed dairy cattle in East Africa. *Frontiers in Genetics*, *5*(DEC), 443–443. https://doi.org/10.3389/fgene.2014.00443

Kirui, J. W., Muthama, J. N., Opere, A. O., & Ngaina, J. N. (2015). Influence of climate change on smallholder dairy productivity: A case of Kosirai, Kenya, and Namayumba, Uganda. *International Journal of Agricultural Science Research*, *4*(6), 109–116.

Kisembe, J., Favre, A., Dosio, A., Lennard, C., Sabiiti, G., & Nimusiima, A. (2019). Evaluation of rainfall simulations over Uganda in CORDEX regional climate models. *Theoretical and Applied Climatology*, *137*(1–2), 1117–1134. https://doi.org/10.1007/s00704-018-2643-x

Lallo, C. H. O., Cohen, J., Rankine, D., Taylor, M., Cambell, J., & Stephenson, T. (2018). Characterizing heat stress on livestock using the temperature humidity index (THI)—Prospects for a warmer Caribbean. *Regional Environmental Change*, *18*(8), 2329–2340. https://doi.org/10.1007/s10113-018-1359-x

Lemerle, C., & Goddard, M. E. (1986). Assessment of heat stress in dairy cattle in papua new guinea. *Tropical Animal Health and Production*, *18*(4), 232–242. https://doi.org/10.1007/BF02359540

MAAIF/ILRI. (1996). *The Uganda Dairy Sub-Sector. A Rapid Appraisal. By International Livestock Research Institute (ILRI) Nairobi, Kenya, Ministry of Agriculture Animal, Industry and Fisheries (MAAIF).*

MAAIF/UBOS. (2010). *National Livestock Census Report 2008*.

Magrath, J. (2008). *Turning up the Heat: Climate change and poverty in Uganda*. *8*(3), 96–125.

Mann, H. B. (1945). Nonparametric Tests Against Trend. *Econometrica*, *13*(3), 245–245. https://doi.org/10.2307/1907187

McSweeney, C., New, M., & Lizanco, G. (2007). *Climate Change Country Profiles: Uganda*.

Ministry of Agriculture Animal Industry and Fisheries. (2011). *National Agriculture Policy*.

Ministry of Water and Environment. (2015). *Uganda National Climate Change Policy*. http://ccd.go.ug

Mubiru, D. N., Radeny, M., Kyazze, F. B., Zziwa, A., Lwasa, J., Kinyangi, J., & Mungai, C. (2018). Climate trends, risks and coping strategies in smallholder farming systems in Uganda. *Climate Risk Management*, *22*, 4–21. https://doi.org/10.1016/j.crm.2018.08.004

Mugisha, A., Kayiizi, V., Owiny, D., & Mburu, J. (2014). Breeding Services and the Factors Influencing Their Use on Smallholder Dairy Farms in Central Uganda. *Veterinary Medicine International*, *2014*, 1–6. https://doi.org/10.1155/2014/169380

Muhanguzi, D., Picozzi, K., Hatendorf, J., Thrusfield, M., Welburn, S. C., Kabasa, J. D., & Waiswa, C. (2014). Prevalence and spatial distribution of Theileria parva in cattle under crop-livestock farming systems in Tororo District, Eastern Uganda. *Parasites and Vectors*, *7*(1), 91–91. https://doi.org/10.1186/1756-3305-7-91

Muller, C. J., & Botha, J. A. (1993). Effect of summer climatic conditions on different heat tolerance indicators in primiparous Friesian and Jersey cows. *South African Journal of Animal Science*, *23*(3), 98–103.

Mutua, J. Y., Marshall, K., Paul, B. K., & Notenbaert, A. M. O. (2020). A methodology for mapping current and future heat stress risk in pigs. *Animal*, *14*(9), 1952–1960. https://doi.org/10.1017/S1751731120000865

Mwanjalolo, M., Bernard, B., Paul, M., Joshua, W., Sophie, K., Cotilda, N., Bob, N., John, D., Edward, S., & Barbara, N. (2018). Assessing the Extent of Historical, Current, and Future Land Use Systems in Uganda. *Land*, *7*(4), 132–132. https://doi.org/10.3390/land7040132

Mwongera, C., Mutua, J., Koech, N., Osiemo, J., Kinyua, I., & Nguru, W. (2019). *Climate risk assessment for selected value chain commodities in Rwanda*.

Mwongera, C., Shikuku, K. M., Twyman, J., Läderach, P., Ampaire, E., Van Asten, P., Twomlow, S., & Winowiecki, L. A. (2017). Climate smart agriculture rapid appraisal (CSA-RA): A tool for prioritizing context-specific climate smart agriculture technologies. *Agricultural Systems*, *151*, 192–203. https://doi.org/10.1016/j.agsy.2016.05.009

Nandozi, C. S., Majaliwa, J. G. M., Omondi, P., Komutunga, E., Aribo, L., Isubikalu, P., & Tenywa, M. M. (2012). Regional Climate Model Performance and Prediction of Seasonal Rainfall and Surface Temperature of Uganda. *African Crop Science Journal*, *20*(s2), 213–225.

National Research Council. (1971). *A guide to environmental research on animals*.

Ndor Fodor, N., Foskolos, A., Topp, C. F. E., Moorby, J. M., Pásztor, L., & Foyer, C. H. (2018). *Spatially explicit estimation of heat stress-related impacts of climate change on the milk production of dairy cows in the United Kingdom*. https://doi.org/10.1371/journal.pone.0197076

Nesamvuni, E., Lekalakala1, R., Norris, D., & Ngambi, J. W. (2012). Effects of climate change on dairy cattle, South Africa. *Africa Journal of Agricultural Research*, *7*(26), 3867–3872.

Nimusiima, A., Basalirwa, C. P. K., Majaliwa, J. G. M., Mbogga, S. M., Mwavu, E. N., Namaalwa, J., & Okello-Onen, J. (2014). Analysis of future climate scenarios over central Uganda cattle corridor. *Journal of Earth Science & Climatic Change*, *5*(10), 237–237.

Notenbaert, A., Herrero, M., Kruska, R., You, L., S., Wood., Thornton, P., & Omolo, A. (2009). *Classifying livestock production systems for targeting agricultural research and development in a rapidly changing world. Discussion Paper No. 19* (pp. 41–41).

Nsubuga, F. W. N., Botai, O. J., Olwoch, J. M., Rautenbach, C. J. deW, Bevis, Y., & Adetunji, A. O. (2014). The nature of rainfall in the main drainage sub-basins of Uganda. *Hydrological Sciences Journal*, *59*(2), 278–299. https://doi.org/10.1080/02626667.2013.804188

Ochwo, S., VanderWaal, K., Munsey, A., Ndekezi, C., Mwebe, R., Okurut, A. R. A., Nantima, N., & Mwiine, F. N. (2018). Spatial and temporal distribution of lumpy skin disease outbreaks in Uganda (2002-2016). *BMC Veterinary Research*, *14*(1), 1–12. https://doi.org/10.1186/s12917-018-1503-3

Olaka, L. A., Ogutu, J. O., Said, M. Y., & Oludhe, C. (2019). Projected Climatic and Hydrologic Changes to Lake Victoria Basin Rivers under Three RCP Emission Scenarios for 2015–2100 and Impacts on the Water Sector. *Water*, *11*(7), 1449–1449. https://doi.org/10.3390/w11071449

Owino, J. O., Olago, D., Wandiga, S. O., & Ndambi, A. (2020). Constraints limiting the improvement of manure management as climate smart technology for smallholder dairy farmers. *African Journal of Agricultural Research*, *16*(8), 1155–1168. https://doi.org/10.5897/AJAR2020.15018

Owoyesigire, B., Mpairwe, D., Ericksen, P., & Peden, D. (2016). Trends in variability and extremes of rainfall and temperature in the cattle corridor of Uganda. *Uganda Journal of Agricultural Sciences*, *17*(2), 231–231. https://doi.org/10.4314/ujas.v17i2.8

Pearce, S. C., Mani, V., Boddicker, R. L., Johnson, J. S., Weber, T. E., Ross, J. W., Rhoads, R. P., Baumgard, L. H., & Gabler, N. K. (2013). Heat Stress Reduces Intestinal Barrier Integrity and Favors Intestinal Glucose Transport in Growing Pigs. *PLoS ONE*, *8*(8), e70215–e70215. https://doi.org/10.1371/journal.pone.0070215

Quandt, A. (2021). Coping with drought: Narratives from smallholder farmers in semi-arid Kenya. *International Journal of Disaster Risk Reduction*, *57*, 102168. https://doi.org/10.1016/j.ijdrr.2021.102168

R Core Team. (2019). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. http://www.r-project.org/

Robinson, T. P., Wint, G. R. W., Conchedda, G., Van Boeckel, T. P., Ercoli, V., Palamara, E., Cinardi, G., D’Aietti, L., Hay, S. I., & Gilbert, M. (2014). Mapping the Global Distribution of Livestock. *PLoS ONE*, *9*(5), e96084–e96084. https://doi.org/10.1371/journal.pone.0096084

Robinson, T., & Pozzi, F. (2011). *Mapping Supply and Demand for Animal-Source Foods to 2030*. Food and Agriculture Organization of the United Nations. https://www.agmrv.org/knowledge-portal/resources/mapping-supply-and-demand-for-animal-source-foods-to-2030/

Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T., & Woznicki, S. A. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, *16*, 145–163. https://doi.org/10.1016/J.CRM.2017.02.001

Rötter, R., & van de Geijn, S. C. (1999). Climate Change Effects on Plant Growth, Crop Yield and Livestock. *Climatic Change*, *43*(4), 651–681. https://doi.org/10.1023/A:1005541132734

Seif, S. M., Johnson, H. D., & Lippincott, A. C. (1979). The effects of heat exposure (31°C) on Zebu and Scottish Highland cattle. *International Journal of Biometeorology*, *23*(1), 9–14. https://doi.org/10.1007/BF01553372

Sempiira, J. E., Katimbo, A., Mugisa, D. J., & Kisaalita, W. S. (2017). Ghee-making in the cattle corridor of Uganda. *African Journal of Food, Agriculture, Nutrition and Development*, *17*(1), 11771–11786. https://doi.org/10.4314/ajfand.v17i1.

Seré, C., & Steinfeld, H. (1996). *World livestock production systems: Current status, issues and trends. Animal Production and Health Paper No. 127*.

Staal, .S.J., & Kaguongo, W. N. (2003). *The Ugandan Dairy Sub-Sector Targeting Development Opportunities*.

Tao, X., & Xin, H. (2003). *Acute Synergistic Effects of Air Temperature, Humidity, and Velocity on Homeostasis of Market-Size Broilers*. http://lib.dr.iastate.edu/abe_eng_pubs/142

Taye, M., Lee, W., Caetano-Anolles, K., Dessie, T., Hanotte, O., Mwai, O. A., Kemp, S., Cho, S., Oh, S. J., Lee, H.-K., & Kim, H. (2017). Whole genome detection of signature of positive selection in African cattle reveals selection for thermotolerance. *Animal Science Journal*, *88*(12), 1889–1901. https://doi.org/10.1111/asj.12851

Thom, E. C. (1959). The Discomfort Index. *Weatherwise*, *12*(2), 57–61. https://doi.org/10.1080/00431672.1959.9926960

Thornton, P. (2010). Livestock production: Recent trends, future prospects. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *365*(1554), 2853–2867. https://doi.org/10.1098/rstb.2010.0134

Thornton, P. K., Enahoro, D., Njiru, N., van Wijk, M., Ashley, L., Cramer, L., Ericksen, P., & Graham, M. (2019). *Program for climate-smart livestock systems. Country stocktake: Uganda*.

Thornton, P., Nelson, G., Mayberry, D., & Herrero, M. (2021). Increases in extreme heat stress in domesticated livestock species during the twenty-first century. *Global Change Biology*, *27*(22), 5762–5772. https://doi.org/10.1111/gcb.15825

Thornton, P., van de Steeg, J., Notenbaert, A., & Herrero, M. (2009). The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agricultural Systems*, *101*(3), 113–127. https://doi.org/10.1016/J.AGSY.2009.05.002

Thornton, Phillip K., Boone, Randall B., & Ramírez Villegas, Julián. (2015). *Climate Change Impacts on Livestock* (Working Paper No. 120). CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). https://cgspace.cgiar.org/bitstream/handle/10568/66474/http://CCAFSWP120.pdf

Tijjani, K. I., & Yetişemiyen, A. (2015). Dairy Cattle and Dairy Industry in Uganda: Trends and Challenges. *Research Journal of Agriculture and Forestry Sciences*, *3*(10), 14–18.

Twecan, D., Wang, W., Xu, J., & Mohmmed, A. (2022). Climate change vulnerability, adaptation measures, and risk perceptions at households level in Acholi sub-region, Northern Uganda. *Land Use Policy*, *115*, 106011. https://doi.org/10.1016/j.landusepol.2022.106011

UBOS. (2019). *Statistical Abstract 2019*. Uganda Bureau of Statistics.

Uganda Bureau of Statistics. (2018). *Statistical Abstract*.

Vitali, A., Segnalini, M., Bertocchi, L., Bernabucci, U., Nardone, A., & Lacetera, N. (2009). Seasonal pattern of mortality and relationships between mortality and temperature-humidity index in dairy cows. *Journal of Dairy Science*, *92*(8), 3781–3790. https://doi.org/10.3168/jds.2009-2127

Voldoire, A., Sanchez-Gomez, E., Salas y Mélia, D., Decharme, B., Cassou, C., Sénési, S., Valcke, S., Beau, I., Alias, A., Chevallier, M., Déqué, M., Deshayes, J., Douville, H., Fernandez, E., Madec, G., Maisonnave, E., Moine, M.-P., Planton, S., Saint-Martin, D., … Chauvin, F. (2013). The CNRM-CM5.1 global climate model: Description and basic evaluation. *Climate Dynamics*, *40*(9–10), 2091–2121. https://doi.org/10.1007/s00382-011-1259-y

Wangalwa, R., Tolo, C. U., Kagoro, G. R., & Wafula, J. (2016). Assessment of on-farm milk handling practices in Mbarara District Southwestern Uganda. *African Journal of Dairy Farming and Milk Production*, *3*(2), 141–1489.

Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., Chikira, M., Ogura, T., Sekiguchi, M., Takata, K., Yamazaki, D., Yokohata, T., Nozawa, T., Hasumi, H., Tatebe, H., Kimoto, M., Watanabe, M., Suzuki, T., … Kimoto, M. (2010). Improved Climate Simulation by MIROC5: Mean States, Variability, and Climate Sensitivity. *Journal of Climate*, *23*(23), 6312–6335. https://doi.org/10.1175/2010JCLI3679.1

Watende, E. (2016). *Perceptions, challeneges and adaptation strategies to climate change and variability: The case of smallholder dairy farming systems in Siaya sub-county, Siaya county*. University of Nairobi.

Wayman, O., Johnson, H. D., Merilan, C. P., & Berry, I. L. (1962). Effect of Ad Libitum or Force-Feeding of Two Rations on Lactating Dairy Cows Subject to Temperature Stress. *Journal of Dairy Science*, *45*(12), 1472–1478. https://doi.org/10.3168/JDS.S0022-0302(62)89658-1

Wichern, J., Descheemaeker, K., Giller, K. E., Ebanyat, P., Taulya, G., & van Wijk, M. T. (2019). Vulnerability and adaptation options to climate change for rural livelihoods – A country-wide analysis for Uganda. *Agricultural Systems*, *176*, 102663. https://doi.org/10.1016/j.agsy.2019.102663

World Bank. (2018). *World Development Indicators database (Population, total (millions)).*

Wurzinger, M., Ndumu, D., Baumung, R., Drucker, A., Okeyo, A. M., Semambo, D. K., Byamungu, N., & Sölkner, J. (2006). Comparison of production systems and selection criteria of Ankole cattle by breeders in Burundi, Rwanda, Tanzania and Uganda. *Tropical Animal Health and Production*, *38*(7), 571–581. https://doi.org/10.1007/s11250-006-4426-0

Yousef, M. K. (1985). *Stress physiology in livestock* (Volume I.). CRC press.

Zumbach, B., Misztal, I., Tsuruta, S., Sanchez, J. P., Azain, M., Herring, W., Holl, J., Long, T., & Culbertson, M. (2008). Genetic components of heat stress in finishing pigs: Parameter estimation. *Journal of Animal Science*, *86*(9), 2076–2081. https://doi.org/10.2527/jas.2007-0282

APPENDIX 1A: Projected Average Relative Humidity (Percent) Changes Based on RCPs 4.5 and 8.5 for the Periods 2021-2050 and 2071-2100 for districts in Uganda

		RCP 4.5		**RCP 8.5**	
District	**Historical**	**2021-2050**	**2071-2100**	**2021-2050**	**2071-2100**

Adjumani	50.8	0.7	0.4	0.6	0.7
Busia	52.6	3.2	3.4	3.1	4.2
Hoima	52.4	1.2	0.7	0.9	0.2
Jinja	57.8	4.0	4.3	3.9	5.0
Kabale	65.0	1.8	1.6	1.6	1.5
Kalangala	67.4	1.0	0.9	0.9	0.8
Kasese	56.8	1.4	0.9	1.2	0.0
Kibaale	62.0	1.9	1.6	1.7	1.8
Kisoro	59.0	1.9	1.5	1.7	1.1
Moyo	48.7	0.5	0.2	0.4	0.2
Ntungamo	63.3	1.9	1.4	1.6	0.9
Ssembabule	64.4	2.5	2.1	2.3	1.7
Kabarole	60.2	1.1	0.7	0.9	0.0
Kaberamaido	48.9	3.6	4.2	3.6	5.7
Kampala	65.7	2.9	2.8	2.7	2.5
Kamwenge	60.4	1.9	1.6	1.7	1.2
Kanungu	52.9	1.5	1.0	1.3	0.1
Kayunga	56.3	4.4	4.8	4.3	5.9
Mayuge	59.2	3.7	3.9	3.6	4.4
Nakasongola	55.7	3.9	4.6	3.8	6.0
Rukungiri	59.5	2.3	1.7	2.1	1.1
Wakiso	65.7	2.9	2.8	2.7	2.5
Yumbe	54.7	-0.3	-0.7	-0.4	-0.6
Amolatar	54.7	3.1	3.8	3.1	5.4
Amuria	44.1	2.7	3.3	2.8	4.3
Butaleja	47.3	3.5	3.9	3.4	5.1
Ibanda	61.7	2.1	1.6	1.8	1.1
Isingiro	65.5	2.4	1.7	2.1	1.0
Kaabong	52.2	1.8	2.7	1.9	3.3
Kaliro	49.9	4.2	4.8	4.1	6.1
Katakwi	43.7	2.7	3.3	2.8	4.3
Kiruhura	63.1	2.3	2.0	2.1	1.6
Koboko	57.4	-0.6	-0.9	-0.7	-0.5
Luwero	58.9	4.1	4.5	3.9	5.3
Mbale	51.7	2.4	3.0	2.4	4.4
Mbarara	63.8	2.2	1.7	1.9	1.3
Mityana	65.2	3.1	3.1	2.9	3.1
Mubende	65.0	2.4	2.3	2.3	2.4
Nakaseke	57.9	3.0	3.5	2.9	4.6
Tororo	50.2	3.0	3.4	3.0	4.6
Budaka	50.0	2.6	3.2	2.6	4.6
Abim	45.4	2.7	3.3	2.7	4.1
Amuru	49.9	0.5	0.4	0.5	0.7
Buliisa	50.9	1.1	0.8	0.9	0.6

Kotido	48.1	2.6	3.5	2.7	4.2
Namutumba	49.6	3.9	4.4	3.8	5.6
Maracha	57.7	-0.3	-0.4	-0.4	0.0
Oyam	56.4	0.9	1.6	1.0	3.3
Dokolo	50.6	3.3	4.1	3.4	5.6
Arua	56.2	-0.1	-0.1	-0.2	0.2
Manafwa	53.3	2.2	2.8	2.2	4.5
Bukedea	48.1	2.2	2.8	2.2	3.9
Bududa	53.9	1.8	2.5	1.8	4.1
Rakai	70.8	1.5	0.8	1.3	-0.3
Lyantonde	66.2	2.4	1.9	2.2	1.3
Amudat	53.6	1.1	1.8	1.2	2.5
Buikwe	63.6	3.6	3.6	3.4	3.8
Buyende	52.2	4.4	5.1	4.4	6.7
Kamuli	56.0	4.2	4.6	4.1	5.6
Kitgum	47.1	1.8	1.9	1.7	2.0
Lamwo	51.3	0.7	0.7	0.6	1.0
Nakapiripirit	48.4	1.7	2.2	1.7	2.9
Nebbi	47.8	0.7	0.2	0.5	-0.4
Otuke	48.1	2.4	2.8	2.4	3.9
Zombo	66.1	0.0	1.0	0.1	2.4
Kyegegwa	63.2	2.2	2.0	2.1	2.0
Kyenjojo	61.2	1.6	1.3	1.4	1.0
Apac	55.7	2.3	3.2	2.4	4.9
Bugiri	52.7	3.8	4.1	3.7	5.0
Bukomansimbi	66.1	2.4	2.0	2.2	1.3
Bukwo	63.0	0.0	1.0	0.1	2.4
Bulambuli	49.8	1.7	2.3	1.7	3.3
Bundibugyo	59.1	1.1	0.7	0.9	0.3
Bushenyi	59.9	1.8	1.3	1.6	0.9
Butambala	66.2	2.6	2.3	2.4	1.8
Iganga	52.0	4.3	4.8	4.3	6.1
Kalungu	67.7	2.2	1.6	1.9	0.8
Kapchorwa	54.6	1.4	2.1	1.5	3.8
Sheema	59.8	2.0	1.4	1.7	0.9
Kole	52.7	1.4	1.9	1.5	3.3
Kween	55.3	1.0	1.8	1.1	2.9
Luuka	55.8	4.2	4.5	4.0	5.4
Masaka	69.5	1.8	1.1	1.5	-0.1
Masindi	52.7	1.5	1.2	1.3	1.3
Moroto	48.7	2.1	3.0	2.3	3.6
Napak	45.7	2.6	3.3	2.7	4.0
Ngora	45.4	3.3	3.9	3.4	5.2
Buhweju	64.1	2.0	1.6	1.7	1.5

Ntoroko	52.2	1.2	0.5	0.9	-0.3
Pader	48.5	1.6	1.8	1.6	2.4
Rubirizi	52.2	1.7	1.1	1.5	0.2
Sironko	53.9	1.8	2.5	1.8	4.1
Soroti	46.2	3.6	4.2	3.6	5.7
Agago	46.1	2.3	2.7	2.4	3.4
Alebtong	46.5	2.9	3.4	2.9	4.7
Buvuma	62.5	1.6	2.0	1.6	2.7
Gomba	65.5	2.5	2.3	2.4	2.0
Gulu	54.5	0.6	1.0	0.7	2.4
Kiboga	62.2	2.8	2.9	2.6	3.4
Kibuku	47.9	3.8	4.3	3.7	5.6
Kiryandongo	58.8	0.8	1.4	0.9	2.8
Kumi	44.7	3.2	3.8	3.2	5.1
Kyankwanzi	58.7	2.1	2.2	1.9	2.7
Mitooma	58.3	1.9	1.4	1.7	0.7
Mpigi	67.4	2.3	1.8	2.1	1.1
Nwoya	53.4	0.4	0.4	0.4	1.1
Serere	47.5	3.6	4.2	3.6	5.6
Lwengo	67.9	2.2	1.7	2.0	1.0
Mukono	62.7	3.5	3.5	3.3	3.8
Namayingo	56.3	3.3	3.6	3.3	4.1
Pallisa	47.8	4.0	4.7	4.0	6.2
Lira	51.2	2.3	2.8	2.3	4.3

APPENDIX 1B: Projected Average Maximum Temperature (°C) Changes based on RCPs 4.5 and 8.5 for the Periods 2021-2050 and 2071-2100 for districts in Uganda

		RCP 4.5		**RCP 8.5**	

District	**Historical**	**2021-2050**	**2071-2100**	**2021-2050**	**2071-2100**
Adjumani	33.3	0.3	1.3	0.5	3.1
Busia	30.2	0.1	1	0.3	2.7
Hoima	32.3	0.1	1	0.3	2.8
Jinja	30.7	0	0.9	0.3	2.7
Kabale	24.2	0.2	1.2	0.5	3.2
Kalangala	26.4	0.3	1.2	0.5	2.9
Kasese	29.4	0.2	1.2	0.4	3
Kibaale	30.3	0.1	1	0.3	2.8
Kisoro	26.5	0.1	1.1	0.4	3.1
Moyo	33.8	0.3	1.3	0.5	3.1
Ntungamo	27.6	0.2	1.2	0.4	3.1
Ssembabule	29	0.1	1.1	0.4	2.9
Kabarole	30.1	0.2	1.2	0.4	3
Kaberamaido	31.9	0	0.9	0.2	2.6
Kampala	28.8	0.1	1	0.4	2.8
Kamwenge	29.4	0.1	1.1	0.4	3
Kanungu	29.4	0.1	1.1	0.4	3
Kayunga	31.3	0	0.9	0.2	2.6
Mayuge	30.1	0	1	0.3	2.7
Nakasongola	31.3	0	0.9	0.2	2.5
Rukungiri	27.5	0.1	1.1	0.3	3
Wakiso	28.8	0.1	1	0.4	2.8
Yumbe	32.6	0.3	1.4	0.6	3.2
Amolatar	31.4	0	0.9	0.2	2.6
Amuria	32	0.1	1	0.3	2.7
Butaleja	31.3	0.1	1	0.3	2.8
Ibanda	28.8	0.1	1.1	0.4	3
Isingiro	28	0.1	1.2	0.4	3.1
Kaabong	28.8	0.2	1.1	0.5	2.9
Kaliro	31.9	0	0.9	0.2	2.6
Katakwi	32.3	0.1	1	0.3	2.7
Kiruhura	28.7	0.1	1.1	0.4	3
Koboko	32	0.4	1.4	0.6	3.2
Luwero	30.8	0	0.9	0.2	2.6
Mbale	28.8	0.2	1.1	0.4	2.9
Mbarara	28.2	0.1	1.1	0.4	3
Mityana	29.4	0.1	1	0.3	2.8
Mubende	29.2	0.1	1.1	0.3	2.9
Nakaseke	31.1	0	0.9	0.3	2.6
Tororo	29.9	0.1	1.1	0.4	2.8
Budaka	29.5	0.2	1.1	0.4	2.9
Abim	31.1	0.1	1	0.3	2.8
Amuru	32.9	0.3	1.3	0.5	3.1

Buliisa	32.6	0.2	1.1	0.4	2.9
Kotido	29.6	0.1	1	0.4	2.8
Namutumba	31.5	0	1	0.3	2.7
Maracha	31.5	0.4	1.4	0.6	3.2
Oyam	31.4	0.2	1.1	0.4	2.8
Dokolo	31.7	0	0.9	0.2	2.6
Arua	31.6	0.3	1.3	0.6	3.2
Manafwa	27.4	0.2	1.2	0.5	2.9
Bukedea	30	0.2	1.1	0.4	2.9
Bududa	27.5	0.2	1.2	0.5	3
Rakai	28	0.2	1.2	0.5	3.1
Lyantonde	28.5	0.1	1.1	0.4	3
Amudat	28.2	0.2	1.2	0.5	3
Buikwe	29.7	0	1	0.3	2.7
Buyende	31.7	-0.1	0.9	0.2	2.5
Kamuli	31.1	0	0.9	0.2	2.6
Kitgum	30.4	0.2	1.2	0.5	3
Lamwo	31	0.3	1.3	0.6	3.1
Nakapiripirit	29.7	0.2	1.1	0.4	2.9
Nebbi	33.1	0.3	1.2	0.5	3.1
Otuke	31.9	0.1	1	0.3	2.7
Zombo	28.1	0.4	1.3	0.6	3.1
Kyegegwa	29.5	0.1	1.1	0.3	2.9
Kyenjojo	29.9	0.1	1.1	0.4	2.9
Apac	31.3	0.1	1	0.3	2.6
Bugiri	31	0	1	0.3	2.7
Bukomansimbi	29.1	0.1	1.1	0.4	2.9
Bukwo	24.3	0.3	1.3	0.6	3.1
Bulambuli	29.2	0.2	1.1	0.4	2.9
Bundibugyo	29.4	0.2	1.2	0.4	3
Bushenyi	28.6	0.1	1.1	0.4	3
Butambala	29	0.1	1.1	0.4	2.9
Iganga	31.6	0	0.9	0.2	2.7
Kalungu	28.7	0.1	1.1	0.4	3
Kapchorwa	27.5	0.2	1.2	0.5	3
Sheema	28.3	0.1	1.1	0.4	3
Kole	31.6	0.1	1.1	0.4	2.8
Kween	27	0.3	1.2	0.5	3
Luuka	31	0	0.9	0.3	2.7
Masaka	28.3	0.2	1.2	0.5	3
Masindi	32.7	0.1	1.1	0.4	2.9
Moroto	29.7	0.2	1.1	0.4	2.9
Napak	30.7	0.1	1	0.3	2.8
Ngora	32	0.1	1	0.3	2.7

Buhweju	27.9	0.2	1.1	0.4	3
Ntoroko	31.8	0.1	1.1	0.4	2.9
Pader	32.1	0.2	1.1	0.4	2.9
Rubirizi	30.3	0.1	1.1	0.4	3
Sironko	27.5	0.2	1.2	0.5	3
Soroti	32.2	0	0.9	0.2	2.6
Agago	31.5	0.1	1	0.4	2.8
Alebtong	32.1	0	1	0.3	2.7
Buvuma	26.8	0.2	1.1	0.5	2.7
Gomba	29.1	0.1	1.1	0.4	2.9
Gulu	31.6	0.2	1.2	0.5	2.9
Kiboga	30.1	0	1	0.3	2.8
Kibuku	31.7	0	1	0.3	2.7
Kiryandongo	31.5	0.2	1.1	0.4	2.8
Kumi	31.6	0.1	1	0.3	2.8
Kyankwanzi	31.2	0.1	1	0.3	2.7
Mitooma	28.5	0.1	1.1	0.4	3
Mpigi	28.7	0.2	1.1	0.4	2.9
Nwoya	32.6	0.3	1.2	0.5	3
Serere	31.9	0	0.9	0.3	2.7
Lwengo	28.1	0.1	1.1	0.4	3
Mukono	29.5	0.1	1	0.3	2.7
Namayingo	29.5	0	0.9	0.2	2.6
Pallisa	32.1	0	0.9	0.2	2.6
Lira	31.6	0.1	1	0.3	2.7

APPENDIX 1C: Projected Average Frequency of Severe Heat Stress (Percent) Changes based on RCPs 4.5 and 8.5 for Periods 2021-2050 and 2071-2100 for districts in Uganda

		RCP 4.5		**RCP 8.5**	
District	**Historical**	**2021-2050**	**2071-2100**	**2021-2050**	**2071-2100**
Adjumani	15.4	-2.1	31.8	5.9	63.2

Busia	0.2	-0.2	-0.2	-0.2	14.4
Hoima	5	-4.1	4.5	-3.1	56.8
Jinja	2.6	-2.4	1.5	-2	46.7
Kabale	0	0	0	0	0
Kalangala	0	0	0	0	1.1
Kasese	0.3	-0.3	-0.3	-0.3	7.4
Kibaale	2.6	-2.6	0.2	-2.2	43.1
Kisoro	0	0	0	0	0.1
Moyo	17	0.3	33.4	8.3	61.5
Ntungamo	0	0	0	0	1.1
Ssembabule	1.2	-1.2	-1.1	-1.2	16.4
Kabarole	1.8	-1.7	0.8	-1.4	27.3
Kaberamaido	2.3	-2.2	0.8	-2	50.1
Kampala	0.6	-0.6	-0.3	-0.6	21.2
Kamwenge	0.7	-0.7	-0.7	-0.7	16.6
Kanungu	0	0	0	0	3.5
Kayunga	4.8	-4.1	4.2	-3.3	61.7
Mayuge	0.7	-0.7	-0.5	-0.7	32.4
Nakasongola	3.1	-2.9	2.1	-2.6	56.2
Rukungiri	0	0	0	0	0.1
Wakiso	0.6	-0.6	-0.3	-0.6	21.2
Yumbe	14.2	-5.5	24.1	0.9	60.2
Amolatar	3.1	-2.9	2.3	-2.6	56.5
Amuria	0.8	-0.8	-0.7	-0.8	32.3
Butaleja	0.6	-0.6	-0.6	-0.6	27.9
Ibanda	0.6	-0.6	-0.5	-0.6	9.8
Isingiro	0.2	-0.2	-0.2	-0.2	5.7
Kaabong	0	0	0	0	1.3
Kaliro	3.3	-3.1	2.3	-2.7	52.7
Katakwi	1.4	-1.4	-1	-1.3	40
Kiruhura	0.7	-0.7	-0.7	-0.7	10.8
Koboko	11.7	-4.2	18.4	0.4	57.4
Luwero	3.3	-3.1	1.8	-2.7	55.4
Mbale	0.2	-0.2	-0.2	-0.2	9.3
Mbarara	0.4	-0.4	-0.3	-0.4	6.4
Mityana	1.2	-1.1	-0.7	-1.1	32.3
Mubende	1.2	-1.2	-1	-1.2	24.6
Nakaseke	3.3	-3.1	2.2	-2.7	56.6
Tororo	0.3	-0.3	-0.2	-0.3	14.8
Budaka	0.2	-0.2	-0.2	-0.2	13.8
Abim	0.1	-0.1	-0.1	-0.1	12
Amuru	8.7	-5.5	17.4	-1.9	63.2
Buliisa	7.1	-3.3	10.2	-1.1	59.7
Kotido	0	0	0	0	1.7

Namutumba	2.1	-2	1	-1.7	41.3
Maracha	8.1	-3.7	13	-0.5	54.5
Oyam	3.3	-3.1	2.1	-2.8	56.6
Dokolo	2	-1.9	0.6	-1.7	50.3
Arua	7.1	-2.9	12	0.2	52.1
Manafwa	0	0	0	0	0
Bukedea	0.1	-0.1	-0.1	-0.1	11.8
Bududa	0	0	0	0	0
Rakai	0.5	-0.5	-0.5	-0.5	14
Lyantonde	0.8	-0.8	-0.8	-0.8	13.7
Amudat	0	0	0	0	1.3
Buikwe	1.3	-1.2	-0.2	-1.2	37.9
Buyende	3.6	-3.3	3.4	-3	57.6
Kamuli	3.3	-3	2.5	-2.6	52.9
Kitgum	0	0	0	0	5.7
Lamwo	0.8	-0.8	-0.3	-0.8	30.9
Nakapiripirit	0	0	0	0	4
Nebbi	6.5	-3.8	14.4	-1	62.3
Otuke	1.7	-1.7	-0.3	-1.6	43.1
Zombo	0.3	-0.3	-0.3	-0.3	11.6
Kyegegwa	1.5	-1.5	-0.6	-1.4	26.7
Kyenjojo	1.8	-1.8	0.4	-1.5	29.5
Apac	2.7	-2.7	1.7	-2.4	55.2
Bugiri	1.4	-1.3	0.2	-1.2	35.7
Bukomansimbi	1.1	-1.1	-0.8	-1.1	22.7
Bukwo	0	0	0	0	0
Bulambuli	0	0	0	0	4
Bundibugyo	1.8	-1.8	0.7	-1.5	25.1
Bushenyi	0.1	-0.1	-0.1	-0.1	4.9
Butambala	0.9	-0.9	-0.7	-0.9	24.2
Iganga	3.5	-3.3	2.5	-2.8	54.6
Kalungu	0.7	-0.7	-0.6	-0.7	18.6
Kapchorwa	0	0	0	0	0
Sheema	0.1	-0.1	-0.1	-0.1	3.7
Kole	2.8	-2.7	1	-2.5	51.8
Kween	0	0	0	0	1.6
Luuka	3	-2.7	2.1	-2.3	49.6
Masaka	0.7	-0.7	-0.6	-0.7	15.5
Masindi	10.7	-3.6	17.2	0	67.6
Moroto	0	0	0	0	2.3
Napak	0	0	0	0	6.4
Ngora	1.6	-1.5	0.2	-1.4	39.4
Buhweju	0.2	-0.2	-0.2	-0.2	3.5
Ntoroko	2.7	-2.6	1.1	-2.2	40.9

Pader	2.5	-2.4	1.1	-2.1	46.7
Rubirizi	0.1	-0.1	-0.1	-0.1	9.9
Sironko	0	0	0	0	0
Soroti	1.9	-1.9	-0.1	-1.7	48
Agago	0.5	-0.5	-0.4	-0.5	24.1
Alebtong	1.7	-1.7	-0.7	-1.6	44.4
Buvuma	0	0	0	0	0.8
Gomba	1.1	-1.1	-0.8	-1	23
Gulu	3.5	-3.4	2.1	-3	55.1
Kiboga	2.2	-2.2	-0.3	-2	43
Kibuku	1.9	-1.8	0.9	-1.6	40.2
Kiryandongo	5.8	-5.1	7.8	-3.7	64.6
Kumi	0.3	-0.3	-0.3	-0.3	27.4
Kyankwanzi	4.5	-4	3.2	-3.3	58.1
Mitooma	0.1	-0.1	-0.1	-0.1	3.7
Mpigi	0.5	-0.5	-0.5	-0.5	17.5
Nwoya	10	-4.3	20.7	0.2	65.4
Serere	2	-2	0.8	-1.8	45.7
Lwengo	0.5	-0.5	-0.5	-0.5	11
Mukono	1.8	-1.6	0.9	-1.4	33.3
Namayingo	0.2	-0.2	-0.1	-0.2	10.8
Pallisa	3	-2.9	2	-2.6	50.8
Lira	1.9	-1.9	-0.2	-1.7	48.7

APPENDIX 2: Projected milk loss due to change in the frequency, intensity, and duration of Moderate and Severe heat stress under future climate conditions (2021-2050 and 2071-2100) under RCP 4.5 and 8.5 scenario; *Units kg/milk/year/dairy cow*

	RCP 4.5	RCP 8.5

District	2021-2050	2071-2100	2021-2050	2071-2100
Adjumani	0.07	0.20	0.10	0.43
Busia	0.96	2.91	1.44	6.46
Hoima	0.06	0.22	0.10	0.52
Jinja	0.61	1.74	0.89	3.82
Kabale	0.00	0.00	0.00	47.71
Kalangala	2.61	21.11	5.61	59.26
Kasese	1.22	4.32	2.00	9.96
Kibaale	0.35	1.30	0.58	3.07
Kisoro	1.31	8.52	2.82	46.20
Moyo	0.14	0.39	0.20	0.85
Ntungamo	3.48	16.76	6.54	41.32
Ssembabule	1.33	4.55	2.11	10.37
Kabarole	0.86	3.19	1.44	7.35
Kaberamaido	0.19	0.52	0.27	1.15
Kampala	1.94	5.99	2.99	13.39
Kamwenge	0.92	3.17	1.49	7.32
Kanungu	1.55	9.37	3.21	24.31
Kayunga	0.33	0.88	0.46	1.90
Mayuge	0.88	2.51	1.29	5.49
Nakasongola	0.30	0.85	0.42	1.87
Rukungiri	2.62	17.05	5.64	44.69
Wakiso	1.94	5.99	2.99	13.39
Yumbe	0.20	0.60	0.29	1.32
Amolatar	0.21	0.63	0.31	1.40
Amuria	0.20	0.59	0.30	1.29
Butaleja	0.49	1.29	0.68	2.74
Ibanda	1.72	6.89	3.00	16.08
Isingiro	2.61	11.31	4.76	26.24
Kaabong	6.10	17.05	8.74	36.71
Kaliro	0.30	0.77	0.41	1.65
Katakwi	0.14	0.40	0.20	0.87
Kiruhura	1.82	6.83	3.10	15.74
Koboko	0.20	0.60	0.29	1.32
Luwero	0.45	1.28	0.64	2.82
Mbale	3.58	23.62	7.68	54.59
Mbarara	2.46	10.66	4.44	25.31
Mityana	1.05	3.28	1.61	7.40
Mubende	1.08	3.60	1.71	8.28
Nakaseke	0.26	0.81	0.39	1.84
Tororo	2.17	13.21	4.40	30.57
Budaka	2.77	17.92	5.87	41.40
Abim	0.79	2.21	1.13	4.82
Amuru	0.18	0.50	0.26	1.10

Buliisa	0.05	0.18	0.08	0.41
Kotido	4.08	10.95	5.75	23.58
Namutumba	0.42	1.09	0.58	2.32
Maracha	0.46	1.39	0.68	3.04
Oyam	0.24	0.80	0.37	1.84
Dokolo	0.15	0.42	0.21	0.92
Arua	0.59	1.78	0.87	3.90
Manafwa	5.18	36.06	11.33	84.05
Bukedea	1.95	11.90	4.04	27.25
Bududa	5.12	34.78	11.17	80.52
Rakai	2.35	8.76	4.01	20.09
Lyantonde	1.76	6.53	2.95	14.87
Amudat	2.89	9.18	4.43	34.83
Buikwe	0.89	2.68	1.34	5.97
Buyende	0.25	0.66	0.34	1.42
Kamuli	0.45	1.28	0.65	2.80
Kitgum	2.21	5.80	3.09	12.40
Lamwo	1.12	2.98	1.57	6.37
Nakapiripirit	2.88	9.61	4.55	21.49
Nebbi	0.06	0.18	0.09	0.39
Otuke	0.28	0.80	0.41	1.77
Zombo	3.79	11.46	5.57	25.09
Kyegegwa	0.91	3.15	1.48	7.25
Kyenjojo	0.79	2.86	1.31	6.63
Apac	0.20	0.61	0.29	1.39
Bugiri	0.64	1.75	0.91	3.77
Bukomansimbi	1.20	3.93	1.91	8.96
Bukwo	0.00	0.00	0.00	43.21
Bulambuli	2.76	17.42	5.84	39.98
Bundibugyo	0.14	0.50	0.23	1.16
Bushenyi	2.17	10.00	4.00	24.26
Butambala	1.27	4.05	1.99	9.18
Iganga	0.35	0.90	0.48	1.90
Kalungu	1.58	5.22	2.53	11.85
Kapchorwa	5.07	33.50	11.02	76.99
Sheema	2.28	11.76	4.41	29.36
Kole	0.27	0.81	0.39	1.81
Kween	2.71	13.18	5.03	40.80
Luuka	0.52	1.43	0.74	3.10
Masaka	1.97	6.79	3.23	15.39
Masindi	0.06	0.19	0.09	0.43
Moroto	2.92	8.12	4.12	17.70
Napak	1.19	3.32	1.70	7.23
Ngora	0.24	0.63	0.33	1.36

Buhweju	2.56	11.56	4.70	27.52
Ntoroko	0.14	0.50	0.23	1.16
Pader	0.37	1.01	0.52	2.20
Rubirizi	0.47	1.69	0.77	3.94
Sironko	5.12	34.78	11.17	80.52
Soroti	0.15	0.42	0.22	0.91
Agago	0.66	1.82	0.95	3.95
Alebtong	0.21	0.60	0.30	1.33
Buvuma	2.16	21.44	5.29	58.26
Gomba	1.22	3.98	1.92	9.08
Gulu	0.26	0.81	0.39	1.82
Kiboga	0.50	1.61	0.77	3.68
Kibuku	0.35	0.92	0.49	1.96
Kiryandongo	0.14	0.49	0.22	1.14
Kumi	0.32	0.85	0.44	1.81
Kyankwanzi	0.17	0.57	0.26	1.32
Mitooma	2.19	11.83	4.32	29.98
Mpigi	1.58	4.95	2.46	11.20
Nwoya	0.12	0.39	0.18	0.89
Serere	0.21	0.57	0.29	1.22
Lwengo	2.19	8.52	3.79	19.37
Mukono	1.54	4.72	2.35	10.55
Namayingo	1.22	4.31	1.99	9.90
Pallisa	0.25	0.65	0.34	1.40
Lira	0.28	0.81	0.40	1.81