UNIVERSITY OF NAIROBI

ASSESSMENT OF CLIMATE RESILIENCE OF TOMATO PRODUCTION USING CLIMATE SMART PEST MANAGEMENT TECHNOLOGIES, UGANDA

By

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I58/36109/2019

A Research Thesis Submitted in Partial Fulfilment of the Requirements for The Award of the Degree of Master in Climate Change Adaptation of the University of Nairobi

AUGUST, 2022

DECLARATION

This thesis is my original work and has not been submitted to any other university.

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DEDICATION

I wish to dedicate this thesis to my late mother, Pinizi Elizabeth, to the N'dakpaze family and Marianist family for their full support throughout my work.

ACKNOWLEDGMENT

I want to express my gratitude to God, the Marianists, and everyone who has contributed in diverse ways to the successful completion of this academic document. My initial gratitude goes to my supervisors, Professor Olago, Professor Dorothy A. Amwata, and Doctor Henri E.Z. Tonnang, for providing the required scientific guidance and supervision. May God bless you all. I am greatly indebted to Food for the Hungry and National Agricultural Research Organisation (NARO-Uganda) and to all the Mbale and Namutumba smallholder farmers in Uganda for their collaboration during the survey. I would not be exhaustive without appreciating Doctor Anani Bruce of the International Maize and Wheat Improvement Centre (CIMMYT), who has encouraged me and assisted me during this study. In addition, I appreciate the contribution of Doctor Michael Mukembo Kidoido from the International Centre of Insect Physiology and Ecology (ICIPE) for his support. Last but not least is the contribution of my classmates, students, teaching staff and the general community of the University of Nairobi and ICIPE.

ABSTRACT

For many years, pest management has been a big problem in Africa, especially in Uganda. Pest proliferation has been exacerbated by climate change. With temperature rise, change in rainfall patterns, and change in humidity and windspeed patterns, the pest's metabolism is modified, increasing their proliferation and resistance to pesticides. Farmers in Uganda for a long time have been using agrochemical products for pest management which are not environmentally friendly. The study was conducted in Mbale and Namutumba, among Uganda's tomato-growing districts. Some of the invasive insect pests recorded during the study were *Tuta absoluta*, spider mite, thrips, aphids, and American bollworms. This study's general objective was to assess tomato production's climate resilience using climate-smart pest management technologies. The three study's specific objectives were, respectively, to determine climate change trends and effects on tomato invasive insect pests; identify opportunities and challenges associated with Climate Smart Pest Management (CSPM) technologies, and assess the perception of smallholder farmers on the role of digital tools in the implementation of CSPM. The study used a mixed research design. The study utilized temperature, rainfall, humidity, windspeed data (1981-2020), and household surveys (N=410). Trend analysis, Mann-Kendall test, Pearson's correlation, and Generalized Linear Model (GLM-quasi-Poisson) were used for data analysis for the first objective while Factor Analysis, percentages, means, and frequencies were used for the second objectives data analysis. For the third objective, expect the percentages, regression analysis was used during data analysis. The data shows that the climate has changed in Mbale and Namutumba, and temperature, rainfall, humidity, and windspeed have contributed to the increase of invasive insect pest occurrence in the districts. The results showed an increasing annual temperature trend in Kampala and Namutumba and some abnormalities in Mbale over the last 40 years by 0.04ºC. The rainfall increased significantly in Kampala (0.24 mm/year) and Mbale (0.0011mm/year), with a significant decrease in the humidity in Kampala and Namutumba with an increased rate of 0.05 m $^{s-1}$ and 0.003 m $^{s-1}$, in Kampala and Namutumba during the study period. Though there was a shifting in humidity pattern in the three districts, the study revealed in Mbale and Namutumba, humidity has decreased with an increase in pests. The concurrent variations in all the variables are likely to have a low effect on the pest occurrence (p= 0.054). This change has affected the tomato farmers in Mbale and Namutumba who turned to CSPM technologies. The study found that CSPM technologies have contributed to the adaptation of climate change effects on tomato production, such as reducing chemical use, decreasing pest density in their farms, and improving crop yield while lowering the environmental pollution. At the same time, our study noticed some key challenges/barriers to the upscaling of CSPM by farmers, such as cultural beliefs, lack of strong publicity from the national government, and lack of good infrastructure like roads and good markets. The results conclude there is a need for providing digital tools to farmers to help sensitise the importance of CSPM technologies and their dissemination and upscale. The study recommends that policies emphasise strengthening the agricultural extension services and supporting the dissemination of CSPM technologies. Capacity enhancement and availability of digital tools and access to agricultural information tailored to the needs of farmers are needed for upscaling CSPM technologies practices.

Keywords: climate change, CSPM, invasive tomato insect pests, resilience, transdisciplinary, Uganda.

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ACRONYMS AND ABBREVIATIONS

CABI	Centre for Agriculture and Bioscience International
CIP	International Potato Center
CO_2	Carbon dioxide
CSPM	Climate Smart Pest Management
DEAPs	District environment action plan
DLG	District Local Government
ENSO	El Niño-Southern Oscillation
FAO	Food and Agriculture Organization of the United States
FGDs	Focus Group Discussions
GDP	Global Domestic Product
ICIPE	International Centre of Insect Physiology and Ecology
ICT	Information and communication technology
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Pest Management
ITCZ	Inter-Tropical Convergence Zone
KIIs	Key Informant Interviews
NARL	National Agricultural Research Laboratories
NARO	National Agricultural Research Organization
NEMA	National Environment Management Authority
PEAP	Parish Environment Action Plans
RCP	Representative Concentration Pathway
SDGs	Sustainable Developmental Goals

UNFCCC	United Nations Framework Convention on Climate Change
UWA	Uganda Wildlife Authority
WID	Wetlands Inspection Division

CHAPTER ONE: INTRODUCTION

1.1 Background

The world human population, according to the World Bank (2019), will grow to 9.7 billion by 2050. This increase is expected to result in high dependence upon natural resources, further threatening the sustainability of agricultural production, already confronted with biodiversity loss, climate change, diseases, and invasive animal and plant pests (Bhattacharjee & Samal, 2020). The food supply projection in 2050 is bringing attention due to the parallel increase within the same time period, of the human population from 7.4 billion to more than 9 billion (Fukase & Martin, 2020). Of 105,000 species studied, if the temperature rise is less than 1.5°C, 6% of insects might be reduced by half from their agro-ecological zones (IPCC, 2021). Variations in rainfall, temperature, and humidity reportedly affect pests' occurrence and prevalence. Under these changes, monitoring and predictions of pest infestations become uncertain in crops such as tomatoes. Data from the Food and Agriculture Organization of the United States (FAO) highlight that 160 million tons of tomatoes are produced yearly (FAO, 2020). The Tomato vegetable crop (*Solanum lycopersicum*) is economically important worldwide, with a 2013 annual yield of 158 million MT from 4.7 million ha (FAOSTAT, 2013). However, according to Stuch *et al.* (2020), there is a decrease in the yield of these crops due to some abiotic constraints, namely an increase in temperature and change in rainfall and humidity. In addition, tomato production is endangered by the attack of *Tuta absoluta* (Zekeya *et al.*, 2019).

In America, scientists used synthetic insecticides to deal with this pest (Desneux *et al.*, 2010). But unfortunately, the use of insecticides becomes an environmental hazard, such as the case in South America. Moreover, Peace (2020), argues that climate change can cause the expansion of pests while migrating from one part to another as a means of adaptation and survival. According to the report of IPCC (2018), there is a likelihood of an increase in temperature, which will result in global warming. Some research shows that the population of pests increased due to global warming that affects the metabolic rate leading to crop destruction (Deutsch et al., 2018). Climate change and variability affect farming and food processing in most African countries. Climate variables have disturbed food farming and processing in most African countries (Adger *et al.*, 2007). In many African countries, according to Amwata (2020), such as Kenya, most smallholder farmers rely on agrochemical products for pest control. Tomato production has a strong and positive socio-economic significance. As there is an increase in climate warming rate, the insect metabolic rate accelerates, which leads to the high consumption of food, hence, their proliferation (Deutsch *et al.*, 2018). In Kenya, total greenhouse gas emissions relative to the Business-As-Usual scenario (BAU), projected to increase from 93.7 M_t CO_2e in 2015 to 143 M_t CO_2e by 2030, are led by agriculture which accounted in 2015 for 40% of the global and national emissions (Government of Kenya, 2020). *Tuta absoluta* was first discovered in Algeria in 2008 in Africa and is now found in almost all African countries (Rwomushana *et al.,* 2019).

The agricultural sector's development is critical to improving Ugandans' socioeconomic lives. In the Eastern part of Uganda, tomatoes are produced by smallholder farmers. The common pests attacking tomatoes are *Polyphagotarsonemus latus*, thrips, aphid mites, and American bollworms (Akemn,1999). Tumuhaise *et al.* (2016), further observes that a new tomato insect pest, *Tuta absoluta*, previously unknown in Africa, spreads widely in the sub-Saharan region, especially in Uganda. Farmers mostly rely on insecticides and pesticides to control the pests, which are not environmentally friendly. To deal with these pests, scientists recommended synthetic pesticides, which are costly and rare in the market (Akemn 1999). The greenhouse gas (GHGs) emissions in Uganda include enteric fermentation and fertilizers, among others, and agriculture alone accounts for 57% of the national emissions (Njeru, 2016). Therefore, it is very important to seek alternative methods of climate resilience for crop production, such as climate-smart pest management (CSPM) technologies. CSPM is an ecosystem approach to controlling pests while reducing the negative human and environmental impacts (Barzman *et al.,* 2015). However, there is a need for a trans-disciplinary approach to integrating technologies to address this issue.

1.2 Problem statement

An increase in population, according to McLennan & Group (2022), results in the exploitation of resources. Many researchers ask whether there will be enough resources to feed nine billion people in 2050 (Malingreau *et al.,* 2012). This increase will result in high dependence on resources, further threatening the sustainability of agricultural production already challenged by ecological degradation, global warming, and flora and fauna pest attacks (Amwata *et al.,* 2021; Bhattacharjee and Samal, 2020). In addition, there is an increase and manifestation of new pests because of global warming, international trade, and other uncertainties (Barzman *et al.,* 2015). Establishing the relationship between the biology of the pests and relative humidity is crucial to understanding the fast colonization of a pest in certain regions (Tamiru *et al.*, 2012). Changes in moisture content can hasten the development of insects while changing the interaction between the pest, their natural enemies, and their hosts (Hayes and Hayes, 2018). Roditakis *et al.* (2018), argues that the effectiveness and efficiency of pesticides used to control increasing invasive pests in the changing climate are questionable since agriculture accounts significantly for greenhouse gas production, it is important to seek alternative methods of climate resilience for crop production. While seeking a sustainable approach, it is essential to implement CSPM (Heeb *et al.*, 2019).

Though numerous studies have been conducted in Uganda (Chepchirchir *et al.*, 2021; Health, 2015; Ntale & Gan, 2004; Tumwine J., 2002), there are still gaps in matters of climate change and invasive tomato pests. First, few substantial studies have been undertaken on the effects of climate change on the occurrence of tomato invasive insect pests on smallholder farmers in Uganda's Namutumba and Mbale Districts. Secondly, very few study has been done on the impacts of CSPM technologies on tomato farmers and how to remedy them (Njeru, 2016; Niassy *et al.*, 2022). Thirdly, there is not much done in terms of research on how digital technologies could help reduce the barriers in the upscaling of Climate Smart Pest Management technologies among tomato smallholder farmers in Uganda. A study carried out by Tambo *et al*. (2019) gave consistent evidence that the use of information and communication technologies (ICT) tools significantly helped farmers to know more about fall armyworms in Uganda and facilitated the adoption of new practices for the management of the invasive pest. Therefore, this transdisciplinary study becomes imperative to strive to contribute to filling in the gaps by assessing the climate resilience of tomato production using climate smart pest management technologies in Uganda.

1.3 Overall and specific objectives

The overall objective was to assess the climate resilience of tomato production using climate smart pest management technologies in Uganda. To achieve this, the following specific objectives were addressed.

Specific objectives

1. To determine climate change trends and effects on tomato invasive insect pests;

2. To identify opportunities and challenges associated with climate smart pest management technologies, and

3. To assess the perception of smallholder farmers on the role of digital tools in the implementation of CSPM.

1.4 Justification and significance of the research

1.4.1 Justification

Farmers opted for pesticides to deal with tomato insect pests that destroy crop yield (Garba *et al.*, 2020; Migeon *et al.*, 2009; Nyangau *et al.*, 2020 Sileshi *et al.*, 2019; Tumwine, 2002). However, according to Chepchirchir *et al.* (2021), the proliferation of invasive tomato pests in Uganda has led to unsuccessful control of these pests putting at risk tomato yield and smallholder farmers livelihoods. Though vegetable crop production is affected by climatic changes, there is less research to establish the link between changes in climate proliferation of invasive pests. Also, the communities lack a proper understanding of the opportunities that come from CSPM technologies, which can help policymakers mainstream CSPM in climate adaptation decision-making. It is useful to evaluate the benefits of digital tools such as radio, video excerpts, and smartphones in crop production on farmers' knowledge, information acquisition for a sustainable management of invasive pests (Tambo *et al.*, 2019).

1.4.2 Significance

A temperature rise and a warm and humid environment cause pest proliferation (M. Khan, 2019; Rahmathulla *et al.*, 2012). This research gives a clear road map of how some climatic parameters influence pests and vegetable production, specifically focusing on the tomato crop. It brings on board farmers through the co-learning process to learn about opportunities and barriers with

CSPM. It highlights opportunities associated with digitalization in pest management to reduce climate change impacts in the sector. The demands of the growing Ugandan population require the national government to adopt sustainable agricultural technologies to minimize tomato yield loss while protecting the environment. This study helped to better mainstream the CSPM technologies at the national level as practical climate resilience solutions for pest proliferation. CSPM technologies are being globally adopted as sustainable community-based solutions in the agricultural sector.

This research will be an eye opener to help regional entities to establish a consortium of organizations to mobilize human and financial resources for a comprehensive investment in regional research for short- and long-term tomato invasive pest control while attaining economic, environmental and social sustainability through the collaboration of global entities like FAO.

1.5 Limitation of the study

The study encountered some challenges to be pointed out. One of such challenges is that because of the lack of information about the exact date of bio-invasion of a pest in Mbale and Namutumba, we assume the dates of recordings of pests' introduction in the regions are taken to be the same date the pests invade Mbale and Namutumba. Some data nature was another limitation of this research. As mentioned above, we used secondary data, which may contain some incomplete information that reduced the accuracy of some analysis outputs.

The Ugandan government regulations about the worldwide coronavirus pandemic and the case of terrorist attacks in the country slew down the research timeframe. Also, due to a lack of good infrastructures like poor roads and network constraints, walking throughout the villages took more time to reach some communities than expected.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter reviews the research on climate change and invasive tomato pests in Uganda, mostly Mbale and Namutumba. The relevance of the literature review takes stock of existing information on the subject matter and establishes what others have written on the subject matter. The review also reveals the extent of research around the farmers' practices to deal with increasing pests. Also, it addresses the sustainability of the current CSPM practices and technologies and the challenges facing farmers in their adoption to suggest how digital tools can be applied in the upscaling. The other part includes the socio-economic implication of insect pests on livelihoods. These factors are relevant to the study because they help draw attention to the alternative side of the over 'romanticized' views about new climate-smart pest management technologies, which obscure the harsh realities. It then leads to the discussions of the way forward to these realities.

2.2 Climate change and variability in Eastern Uganda

The United Nations Framework Convention on Climate Change (UNFCCC), highlights climate change as an alteration of climate by anthropogenic action modifying the atmospheric composition over 30 years in addition to natural climate variability (United Nations, 1992). The Inter-Tropical Convergence Zone (ITCZ), monsoonal winds, and El Niño–Southern Oscillation (ENSO) (Ntale and Gan, 2004) influence the climatic condition of Uganda. Uganda has two rainfall seasons: unimodal in the north from June to August, bimodal from March to May and the shortest one in September to November in the equatorial region (Kisembe *et al.*, 2019). Evaporation is more than the rainfall average of 1215 - 1238 mm during dry months (Chombo *et al.*, 2018). The altitude that is above the sea level ranges from 914 m.

Drought, changes in precipitation patterns, and floods negatively impact humans and the environment in Mbale and Namutumba. Humans influence the climate system, and recent climate-induced variability already results in overall impacts on the human environment, according to IPCC (IPCC, 2014; Amwata and Snelder, 2021). Climate change models predict significant temperature rise in the eastern part of Uganda, such as Uganda, influencing pests' pressure and migration patterns and calling for sophisticated management practices by smallholder farmers for pest control (Botha *et al.*, 2020). According to Macleod and Caminade (2019), changes in the climatic patterns have affected the biology of pests in temperate and high-altitude areas. The periodic temperature will likely upsurge by three-degree Celsius under the Representative Concentration Pathway (RCP) 8.5 scenarios across Uganda for the next eight decades (Wichern *et al.,* 2019). According to the IPCC (2018), global warming is expected to reach 1.5°C between 2030 and 2052. The temperature rise indicates pest growth and proliferation due to the warm environment. The Districts of Mbale and Namutumba are fed by Lake Kyoga Basin (Chombo *et al.,* 2018). The Lake Kyoga Basin is dominated by the Nile River current, though the most dominant water resource in Uganda is Lake Victoria. The surface area of Lake Kyoga is 2636 km^2, with a mean elevation above sea level of 1034 m (Wichern *et al.,* 2019). Rivers drain the lake from the Ugandan side of Elgon Mountain and the country's central highlands.

2.3 Crop production and socio-economic implication in Uganda

Agriculture is a key sector for socio-economic growth in Uganda and other African countries. It reduces poverty while attaining the Sustainable Development Goals (Gomez, 2020). Uganda, specifically Eastern Mbale and Namutumba Districts, produces the major subsistence crops such as plantain banana, maize, sweet potatoes and tomatoes. There is a large consumption of these crops at the household level, and these crops contribute to up to 72 per cent of employment (Gouldson, 2017). The Ugandan land area under the agro-ecological zone that is suitable for tomato production is 10,154 Km^2 (McDonagh and Bahiigwa, 2002). Much of this land is used by households for rainfed farming; the main managers of the farming and livestock keeping are men who are the caretakers of the households (Akram-Lodhi, 2018; Sell & Minot, 2018). Farmers are exposed to the issue of disease and pest management. The tomato crop is widely produced for revenue. Its production has a major role in reducing food insecurity in Uganda while improving the livelihoods of smallholder farmers (Tusiime, 2019). According to the projections, as observed by Kikoyo & Nobert (2016) in Uganda, one of the impacts of climate change is temperature rise and alteration in rainfall patterns. The rainy season favors the proliferation of pests and diseases, such as *Tuta absoluta,* which is considered the most threatening crop pest currently due to the level of damage it causes (Dube *et al.,* 2020). Özkara (2016), argues that the reliance on pesticides to manage tomato insect pests is not environmentally friendly and hazardous to human health which is an ecological concern (Tusiime, 2019). There are issues of economic concern regarding the reliance on pesticide use for pest management. Atuhaire (2016) argues that the accessibility and cost of pesticides are becoming more expensive to farmers, while their inefficient use is health hazardous. The pests have become more resistant. The dominant presence of invasive species has destroyed the efficacy of the natural enemies. The liberalization of agrochemicals in sub-Saharan Africa does not favor mainstreaming new technologies (Williamson, 2003). Farmers constantly exposed to the chemicals develop health issues and have little income to support their families (Mutumba, 2018).

The population surrounding Kyoga plains, with high poverty and food insecurity index, has a high population growth rate of 4% - 6% (Chombo *et al.*, 2020). Though the Eastern part of Uganda has important biophysical resources such as vegetation, freshwater, and crops, it is impacted by socio-economic indicators like health, population, poverty, and food insecurity (Chombo *et al.*, 2020). These socio-economic indicators associated with unrestrained wildfires due to the clearance of the land for crop production increased the alarming situation about climate impacts on tomato production.

2.4 Invasive pest species and effects of climate on pests in Uganda

Some researchers explain that from around early 1980, Uganda was threatened by invasive species that destroyed many crops (Rwomushana *et al.*, 2019). Most exotic pests have adapted to the environment, which is more suitable for their reproduction while reproducing in high numbers. Plant trade and travel commodities facilitate the spread of some species, and those species adapt easily to their new environment because of favourable climatic conditions (Sileshi *et al.*, 2019). According to some scientists, Thrips pests that could have originated from the Mediterranean have been causing damage by spreading the Tomato Spotted Wilt Virus (TSWV) in Uganda (Ssemwogerere *et al.*, 2013). Global warming influences the food availability, the density of pests, and the virulence of new pest stains, leading to outbreaks due to the instability of the pest population (War *et al.*, 2016). Tomato late blight (*Phytophthora infestans*) has also been an invasive species that has been destroying tomato production in Uganda. Its first appearance in Uganda in 1995 (type A1) was challenging for the farmers for its control because they were mostly relying on fungicides which were barely available due to the high cost (Tumwine, 2002). Despite many ways to reduce bio invasion, there are new exotic pests recorded yearly.

From the European and Mediterranean Plant Protection Organization (EPPO) available at (https://www.eppo.int/), the Global Biodiversity Information Facility (GBIF) (https://www.gbif.org/), and the Centre for Agriculture and Bioscience International (CABI) (https://www.cabi.org/) the invasive pests that have been recorded in Uganda and which have tomato as their host plant from decades up to now are *Tuta absoluta, Bemisia tabaci Gennadius, Zeugodacus cucurbitae/Bactrocera invadens (spp, Thrips parvispinus (THRIPV), Thrips hawaiiensis, Thaumatotibia leucotreta, Sternochetus mangifera, Spodoptera littoralis, Spodoptera frugiperda, Scirtothrips dorsalis, Nipaecoccus viridis, Aleurotrachelus atratus Hempel, Aphis craccivora, Aphis gossypii, Aspidiotus destructor, Bactrocera cucurbitae, Bagrada hilaris, Ceratitis rosa, Dacus bivittatus (fruitfly Bigot, 1858), Dacus ciliates, Dysmicoccus brevipes, Dysmicoccus neobrevipes, Ferrisia virgata, Forficula Auricularia, Frankliniella occidentalis, Helicoverpa armigera, Hemiberlesia lataniae, Hypothenemus hampei, Insignorthezia insignis, Liriomyza sativae, Macrosiphum euphorbiae, Myzus persicae*. The Generalized Insect Life-System Model, according to Taylor *et al.* (2018), indicates the influence of some abiotic factors like precipitation; the temperature affects pests' mobility. Thermal Extremes bring differences in pest populations at all levels (Ma *et al.*, 2021). Pest response to increasing temperatures impacts the amount of damage to crops (Lehmann *et al.*,2020). Temperature influences insects' development, distribution, and phenology (Ziska *et al.*, 2018). The proliferation of *Tuta absoluta* is increasing within tomato farming regions (Kansiime, 2020). The ectothermic condition of pests makes them more sensitive to the change in temperature because of the trophic relationship as organisms (Deutsch *et al.*, 2008).

Therefore, the climatic trends harm the yield production of tomato crops (Lobell and Field, 2007). As the temperature rise, the environment becomes humid and warm, favoring pests' rapid growth and proliferation (Chivian, 2000). When the season becomes warmer, it gives more time for pests to develop, eat the plants and more time to produce another generation (Bisbis *et al.*, 2018). Farmers in Uganda are unaware of the real impact of this tomato pests *Tuta absoluta*, a tiny insect that eats leaves, fruits, and even flowers (Kansiime, 2020). Experts believe that rising temperatures and erratic rainfall lead to more intense invasions in the spread of *Tuta absoluta* over some African regions. Therefore, increased offspring number due to higher temperatures is associated with pest outbreaks. *Tuta absoluta* can withstand extreme temperatures (Machekano *et al.*, 2018).

2.5 Common pest control practices and digital technology implication

For a long time, farmers relied on pesticides and herbicides to deal with pests in Uganda. However, pesticides are becoming less useful with negative climatic conditions like increasing carbon dioxide (CO_2) (Matzrafi, 2019). Also, pesticides contain chemicals that are not environmentally friendly, and hence they are hazardous to water, soil, vegetation, human health and other species (Özkara, 2016). More insecticide use brings issues of pest resistance, human health and ecosystem damage and the high cost of pesticide acquisition (Deutsch *et al.,* 2018). Studies by Pretty and Bharucha in Africa and Asia (2015) elaborated that Integrated Pest Management has shown efficacy in reducing pesticide use with a concomitant increase in crop yields. Experts from The International Potato Center (CIP) used integrated pest management (IPM) in their fight against Potato Late Blight and a participatory approach to ease the farmers' information, technology, and knowledge access (Ortiz *et al.*, 2019).

Recent studies in pest management acknowledge Push-Pull technology as efficient in controlling the cereal stem borer and *Striga* and in improving soil fertility (Hailu *et al.*, 2018). According to Khan *et al.* (2016), Push-Pull is a cropping system that uses one organism to repel the pest attracted by another organism through the emission of semio-chemicals.

In India, New Delhi, E-National Pest Surveillance, integrated ICT for the control of pulse pests (Alam *et al.*, 2016). In Uganda, ICT and radio have successfully been used as information channels to help farmers to know more about Fall Armyworm and the sustainable ways of dealing with the pest (Tambo *et al.*, 2019). However, there is less emphasis on the importance of CSPM to cope with these devastating impacts and less ICT implication in tomato pest control.

2.6 Climate smart pest management as an agro-ecological approach

Agro-ecological approach fills the gap that has been created between an ecological and social dimension in yielding production resilience to climate related issues (Caron *et al.*, 2014). CSPM is a multi-sectoral approach to reducing pest-induced crop losses and improving ecosystem services. It also reduces the intensity of greenhouse gas emissions per unit of food grown and reinforces agronomic systems' resilience to climate change (Heeb *et al.*, 2019).

According to Wezel *et al.* (2018), the agro-ecological approach is considered one of the most effective transdisciplinary action-oriented approaches because it captures the science, political and socio-economic dimensions with sustainable and reliable practices. According to the study, this approach has different principles, such as input reduction and co-creation of knowledge, whether small or large scale, field or the whole system. In Malawi, for example, agro-ecology has been used to test the efficacy of some practices in climate smart agriculture (Kerr *et al.,* 2018). Some of the CSPM technologies are push pull, parasitoids, biopesticides, monitoring, botanical extracts. Parasitoids and push pull for example have been efficient in Kenya and Zambia.

2.7 Regulatory framework

Districts in Uganda like Mbale and Namutumba, work to guarantee the availability of good services to communities through transparent local governance (Government of Uganda, 2021; Nakayi, 2018). In 2003, its local governance put an Environment Action Plan into place, derived from the National Environment Act CAP153 section 18. Parish Environment Action Plans are used to prepare the District Environment Action Plan (DEAP) (National Environment Management Authority, 2009). According to the report, Uganda coordinates activities from the National Environment Management Authority (NEMA), Wetlands Inspection Division (WID), and Uganda Wild Life Authority (UWA).

2.8 Theoretical framework

Two theories have been found useful in this research. They help to understand the nuances involved in climate smart pest management while supporting the study.

2.8.1 Securitization Theory

According to Buzan et al., (1998) securitization of a country, in the traditional sense, happens when there is a security threat and emergency. In this 21st century, climate change is considered as a worldwide threat to the environment as well as to humanity. The impact of climate change is a risk not only to national, regional and global food security but also to human and environmental health.

Therefore, this theory sustains the fact that climate change is a threat to tomato production farmers which need discussion in order to find sustainable solutions to the issues it brings about as done within this paper.

2.8.2 Technology Acceptance Model

Fred Davis in 1989 conceptualized this theory to assess reception of information or technologies. It helps to find out the potentiality of an individual to upvote a certain system that might improve his/her action and also to perceive if the endorsement of the system could be influenced by some factors. Therefore, how tomato farmers perceive the usefulness and ease of use of the CSPM technologies on adaptation to climate change influences their adoption.

2.9 Conceptual framework

The conceptual framework according to Varpio *et al.* (2020), justifies any research study while bringing out the unsolved problems and the methodological approach used to tackle the problem. Global warming alters the temperature, rainfall, windspeed and humidity patterns. As temperature rises, seasons become warmer in some regions. It provides a perfect environment for some pests to migrate and colonize in some regions.

As indicated in the conceptual framework, Climate change brought temperature, rainfall, and humidity changes. The changes in the climatic patterns provide a perfect environment for some pests to migrate and colonize in some regions, putting them at risk of tomato production. Conventional practices such as agrochemicals become ineffective since pests have built resistance to these agrochemicals. It results in socio-economic and biophysical impacts such as environmental and health degradation, yield loss, and famine. Today's approach encourages a transdisciplinary approach to problem-solving. Therefore, sustainable practices and models are essential to build climate tomato farmers' resilience. The research focused on how CSPM technologies can enhance the resilience of tomato smallholder farmers while improving human and environmental health, as shown conceptually in **Figure 2.1**. The framework highlights the opportunity digitals tools can be used to enhance CSPM adoption.

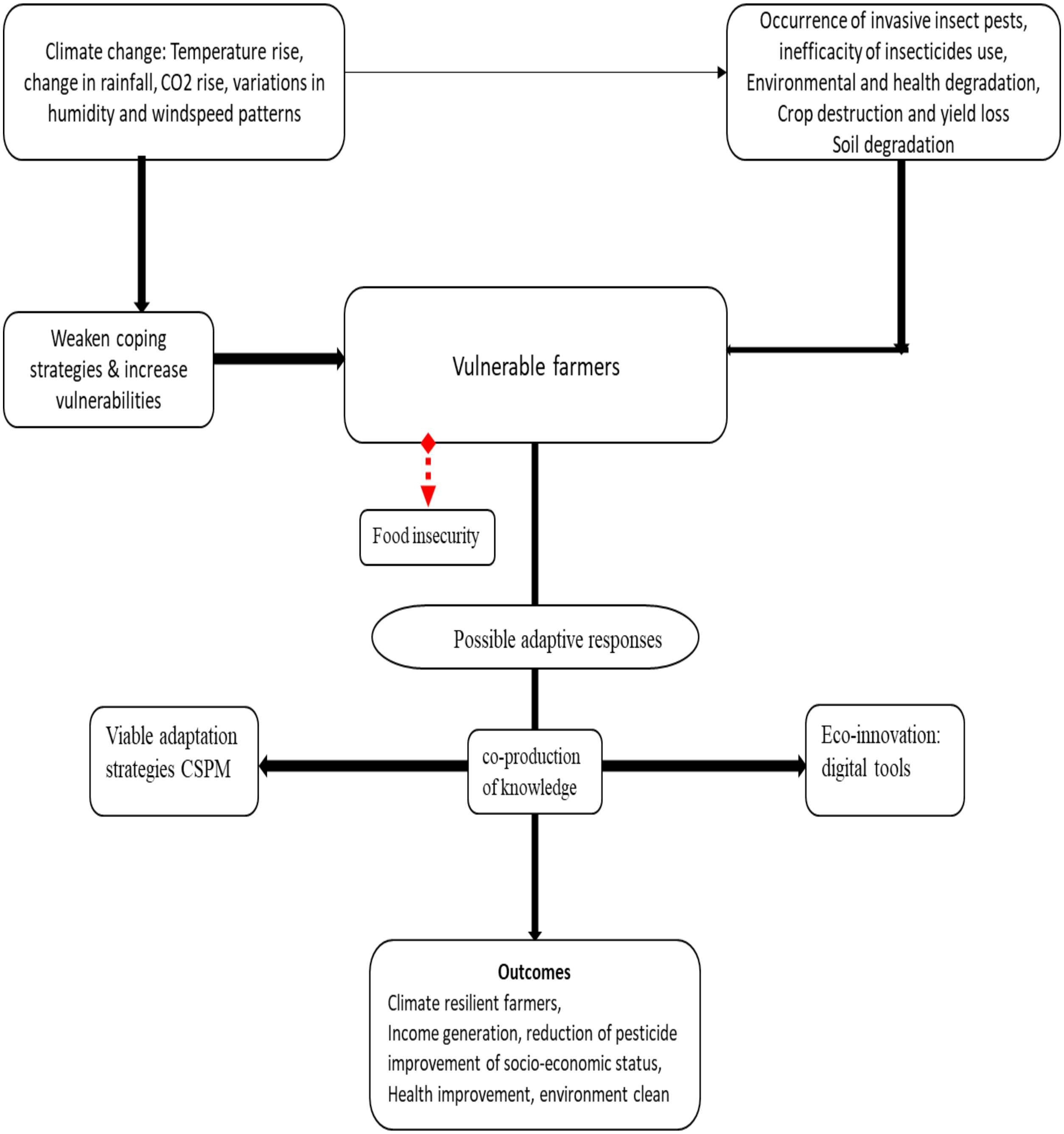


Figure 2.1: conceptual framework

Source: Author, 2022

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter presents the process through which the research data and information have been collected and generated to make decisions and the consequent analysis. The chapter describes the study area and population of the smallholder farmers concerned in the research. The chapter also defines the methods by which knowledge was gained, the work plan of research design and the limitations of the study.

3.2 Study area

The research was conducted in Mbale and Namutumba, the Eastern part of Uganda. Uganda is situated in the Eastern part of Africa **(Figure 3.1)**. It is a landlocked country bordered in the North by Sudan, Kenya to the west, to the South by Lake Victoria, Rwanda, Tanzania, and finally, the Democratic Republic of Congo. Uganda lies between 0.5^{o}N latitude and 32.0^{o}E longitude, with an elevation of approximately 1136.77 meters above sea level (https://power.larc.nasa.gov/).

Though we used Kampala as the reference point, two districts known for tomato production were assessed to compare the impact. The two districts were Mbale (34.181^{o}E, 1.0784^{o}N) and Namutumba (33.6861^{o}E, 0.8361^{o}N). The coordinates represent the centroids of the districts.

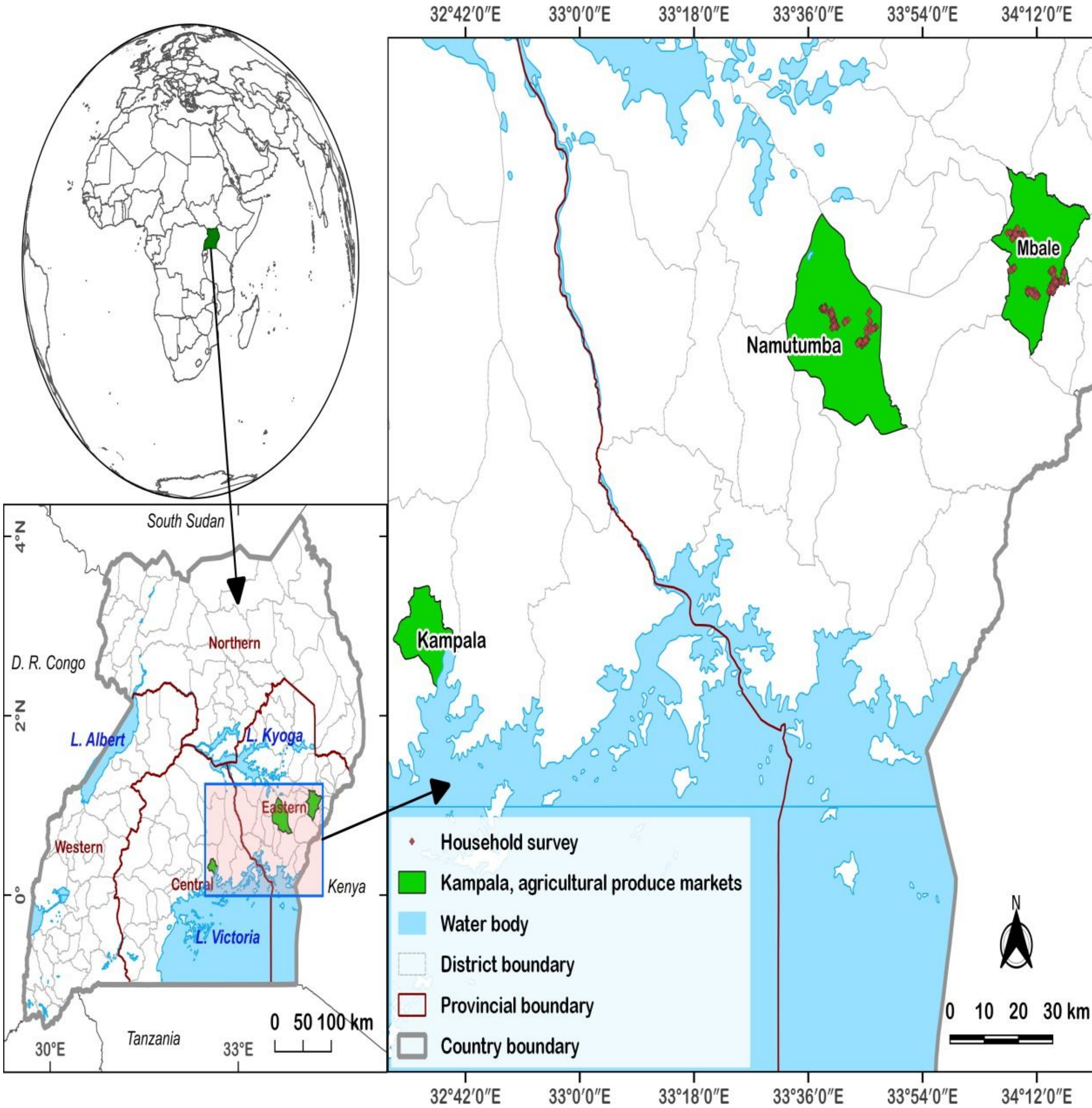


Figure 3.1: Map of Uganda with study area

Source: Author, 2022

3.3 Research design

Mbale and Namutumba have been chosen for the study because the districts are among the most known areas for tomato farming. Primary and secondary data collection methods were used. Primary data were collected in the field while secondary data were obtained from online documents and from the National Environment Management Authority, National Agricultural Research Organization, International Centre of Insect Physiology and Ecology, Food for the Hungry, National Agricultural Research Organization (NARO), Uganda and other collaborative Organization working in both Districts such as Food for the Hungry.

Primary data were household surveys of tomato smallholder farmers in both districts, Mbale and Namutumba. Climate data (annual mean temperature, total annual rainfall, annual average humidity and windspeed) have been retrieved from NASA power (https://power.larc.nasa.gov/data-access-viewer/) at a spatial resolution of 0.5x0.625-degree latitude/longitude. The data on the invasive insect pests were secondary data obtained from online databases such as the European and Mediterranean Plant Protection Organization (EPPO) available at https://www.eppo.int/, the Global Biodiversity Information Facility (GBIF) (https://www.gbif.org/), and the Centre for Agriculture and Bioscience International (CABI) (https://www.cabi.org/) (Brunel *et al.*, 2010; Osdaghi, 2020).

3.4 Study population

This study's respondents were smallholder farmers households who cultivated tomatoes in the Eastern part of Uganda, Mbale and Namutumba. According to 2012 survey statistics, the population of Mbale and Namutumba districts were 441300 and 218900. In this context, the study proceeded with questionnaires. Primary data were collected from 410 households in Mbale and Namutumba. Secondary data were collected because, according to Martins *et al.* (2018), the secondary research methodology and techniques allow involvement in collecting data from existing resources.

3.5 Sampling procedure

O'Leary (2004) says that, for generalization purposes, a sample should meet the requirement of both relevance and representativeness. Out of beneficiary farmers in the Eastern part of Uganda (around 9000 tomato farmers target from ICIPE) of CSPM technologies on the project of Eastern Uganda where CSPM technologies were implemented, 410 households (210 from Mbale and 200 from Namutumba) were selected for the survey. Snowball sampling method was used to detect and interview farmers after using purposive sampling to select the communities. These two methods were used because the research timing coincided with the peak of the coronavirus pandemic and cases of terrorist attacks in the country making respondents quite difficult to access due to security issues. These reasons made the two sampling techniques most appropriate to use. According to O'Leary (2004), Snowball sampling is often used when dealing with populations that are inaccessible or difficult to identify.

3.6 Methods of data collection and analyses

The Mann-Kendall test and the Generalised Linear Model were used to analyse the first objective. Mann Kendall trend (MK) test was used to establish trends in climate variables from 1981 to 2020 and document trends in the occurrence of new invasive pests. The MK trend method, was used on the climatic variables to assess the negative or positive tendency in the level of temperature, rainfall, relative humidity, and windspeed over the years (Fan *et al.*, 2020; Gadedjisso-Tossou *et al.*, 2021; Ngoma *et al.*, 2021). The MK test is commonly used for environmental and climate data to understand the significance level of the tendency in time series data within a location and to establish the occurrence of climatic changes (Alemu and Dioha, 2020; Osman *et al.*, 2021). Specifically, the analysed data provided insight into whether there is a significant increase or decrease trend in the historical time series of the chosen variables: temperature, rainfall, relative humidity, and windspeed. The trends can be negative, non-null, or positive. When there is a positive value of the MK test, there is an increasing trend, while the opposite shows a decreasing trend (Chatziefstathiou *et al.*, 2020; Karuri *et al.*, 2017).

The statistical equation (1) of the MK test is given:

$$\sum_{a=1}^{n-1} \sum_{b=a+1}^{n} sign = (x_b - x_a)\ (1)$$

..........Equation 1

With:

x_b= the value of the climatic variable (temperature, rainfall, relative humidity, or windspeed) data at time b (second time step e.g., 1982)

x_a= the value of the climatic variable (temperature, rainfall, relative humidity, or windspeed) data at time a (initial time e.g., 1981)

$$sign\ (x_b - x_a) = \begin{cases} 1, if\ \ (x_b - x_a) > 0 \\ 0, if\ (x_b - x_a) = 0 \quad (2) \\ -1, if (x_b - x_a) < 0 \end{cases}$$ ……………………………………………………Equation 2

The Sen's slope test gave the statistical significance of the tendency in climatic variables over time (Alahacoon *et al.*, 2022; Gebrechorkos *et al.*, 2019). For a set of pairs (a, x_a) the Sen's slope equation is:

$$\frac{x_b - x_a}{b - a} (3)$$ ………………………………………………………………………………………………… .Equation 3

The association between climate variables and pest occurrence is analysed using Pearson's correlation. The effect of climate variables on pest invasion over the years was assessed using a GLM because the data was 'count data' (Gowsar *et al.*, 2019; Seavy *et al.*, 2005). This model predicted pest occurrence and was well suited for our count data (Maxwell *et al.*, 2018). The determination of normality of pest count was obtained through the Shapiro test. After that, the GLM was run using the entire dataset occurrence in R-software using the 'package' 'quasi-poisson' in order to establish the effects of the climate variables, i.e., temperature, rainfall, relative humidity, or windspeed on the occurrence of invasive insects' pests (R Core Team, 2020). Finally, equation 4 brought out the impact of the climate variables over the years on the occurrence of new pests in Uganda. Quasi-Poisson models perform best when the data dispersion is not close to one assumed by the Poisson model. Equation 4 is as stipulated:

$$E\ (Y) = \mu = exp(\ \beta o + \beta 1x1 + \ \beta 2x2 + \cdots)(4)$$ … … … … … … … … … … … … .. Equation 4

Where:

- μ is the Quasi Poisson variance function.
- *exp (β)* is the expression impact any independent variable could have on the mean.
- βs represents any expected change in the **log of the mean** per unit change in x

The Quasi-Poisson GLM in R software is: glm (formula = Count ~ the value of the climatic variable (temperature, rainfall, relative humidity, or windspeed) data, family = quasi-poisson (link= log)).

Secondary data were collected using Open Data Kit (ODK) platform to address the second and third objectives. The type of data that were analyzed for both objectives were socio-demographics, challenges and opportunities in using CSPM technologies, ownership of digital tools, perception on the importance of digital tools in the adoption of CSPM. The study's qualitative and quantitative data were both analyzed. In order to have quality data, questionnaires were numbered. After data collection, data was cleaned in order to remove any discrepancies, omissions before analysis. The analyzed data was presented in percentages, means, and frequency forms. During the data presentation, descriptive statistical tools such as graphs, charts, and percentages were used.

Another statistical analysis performed was Factor Analysis (FA) from primary data collected. Factor analysis is an important multivariate statistical tool commonly used to evaluate tests, scales, and measures (Williams *et al.*, 2012). Factor analysis was conducted to reduce the dimensions of factors and give better suggestions of opportunities when making operational decisions concerning CSPM. Variance, eigenvalue and factor score are important concepts when utilizing FA. The variance helped in discovering the influence among the variables and communalities which are the proportion of shared variability should be greater than 0.7 or at least 0.6 (Field, 2005). According to Kaiser's recommendation, a component with an eigenvalue of 1 or above and is more useful in decision making hence, any opportunity with eigenvalue of 2.1 as well as any challenge with eigenvalue of 2.5 captures most variance (Field, 2005). The cumulative variability of significant components, according to Williams et al. (2012), is commonly between 50-60%. The extraction method used was Principal Component Analysis (PCA), and the Eigenvalue contributes to the significance of extracted factors (Niranjan, 2004). FA was run using SPSS software (Field, 2005).

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results of the study. The findings are discussed and presented on the themes of the study objectives. The results and findings cover climate change trends and effects on tomato invasive insect' pests' occurrence, opportunities and challenges associated with conventional adaptation strategies and CSPM technologies, and the role of digital tools in implementing CSPM.

4.2 Climate change trends and effects on tomato invasive insect' pests' occurrence

4.2.1 Assessment of the occurrence of the tomato pests

The Mann Kendall test showed a significant increase in the occurrence of tomato new pests over the last 40 years (n=40) (**Figure 4.1)** (period 1981-2020).

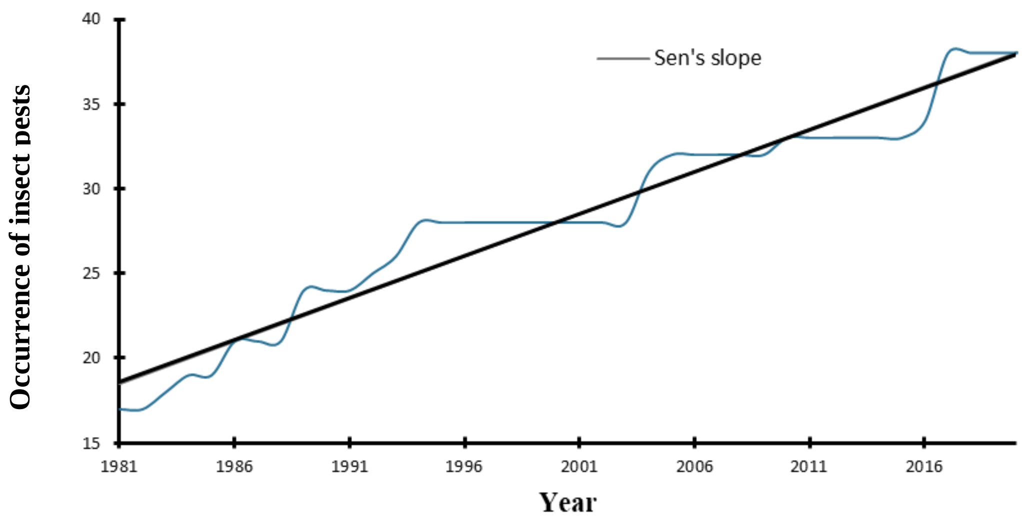


Figure 4.1: Occurrence of tomato invasive insect pests from 1981 to 2020 in Uganda

Figure 4.1 demonstrates a trend analysis showing a statistically significant rise of invasive insect's pests over the years. With a $p<0.0001$ with a Sen's slope test results, there is a likely occurrence of one pest each two years.

4.2.2 Determination of trends in temperature

Table 4.1 and **Figure 4.2**, illustrates respectively MK and Sen's slope test for the mean annual temperature for the three Districts. The Districts of Kampala ($p<0.0001$) and Namutumba

(p=0.006) experienced statistically significant increments of 0.049^{o}C and 0.037^{o}C per year, respectively. Over the years, we observed a small decrease (0.002^{o}C) with no significance in the trend variation of mean temperature in Mbale (p=0.894). The highest increase in temperature occurred in Kampala between 1981 to 2020 at 0.049^{o}C yearly **(Table 4.1)**.

Table 4.1: Estimated Sen's Slope values for the temperature variable' trends from 1981 to 2020 in the regions

Districts	Range		Sen's Slope	*p*-Value
	Minimum	**Maximum**		
Kampala	21.28	24.68	0.049	< 0.0001
Mbale	17.43	21.51	-0.002	0.894
Namutumba	22.84	27.87	0.037	0.006

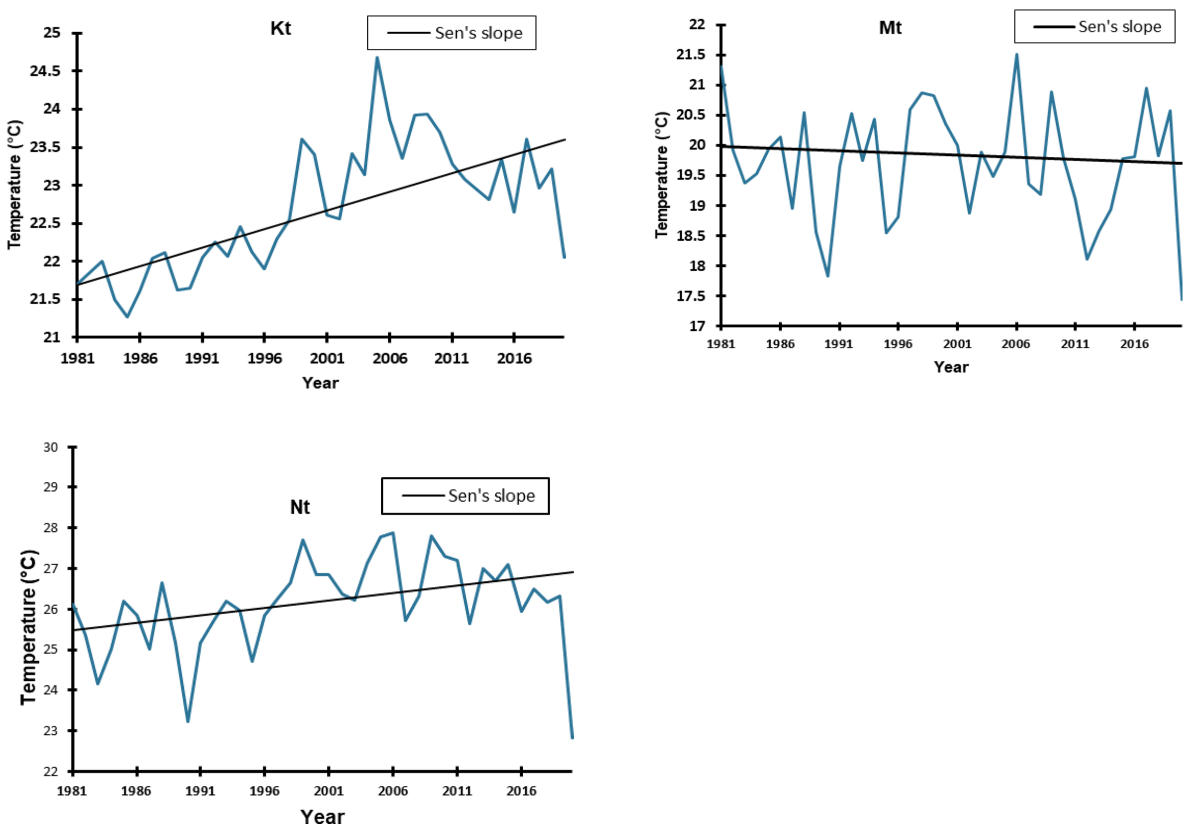


Figure 2.2: Trends in annual mean temperature in Kampala (Kt), Mbale (Mt) and Namutumba (Nt) Districts.

4.2.3 Estimation of trends in rainfall

Results for the annual rainfall for the three Districts are shown in **Table 4.2** and **Figure 4.3**, respectively. There were statistically significant increments in Kampala (*p*=0.029) and Mbale (*p*= 0.0011), respectively, by 0.241mm and 9.804mm per year.

There was no significant trend in Namutumba (*p*=0.394). However, there was an increase in rainfall by 0.025 mm per year. Overall, there was an increase in rainfall in the three Districts (**Table 4.2**).

Table 4.2: Estimated Sen's Slope values for the rainfall trends from 1981 to 2020.

Districts	Range		Sen's Slope	*p*-value
	Minimum	Maximum		
Kampala	923.92	1602.92	0.241	0.029
Mbale	1187.88	2341.03	9.804	0.0011
Namutumba	1174.05	2144.79	0.025	0.394

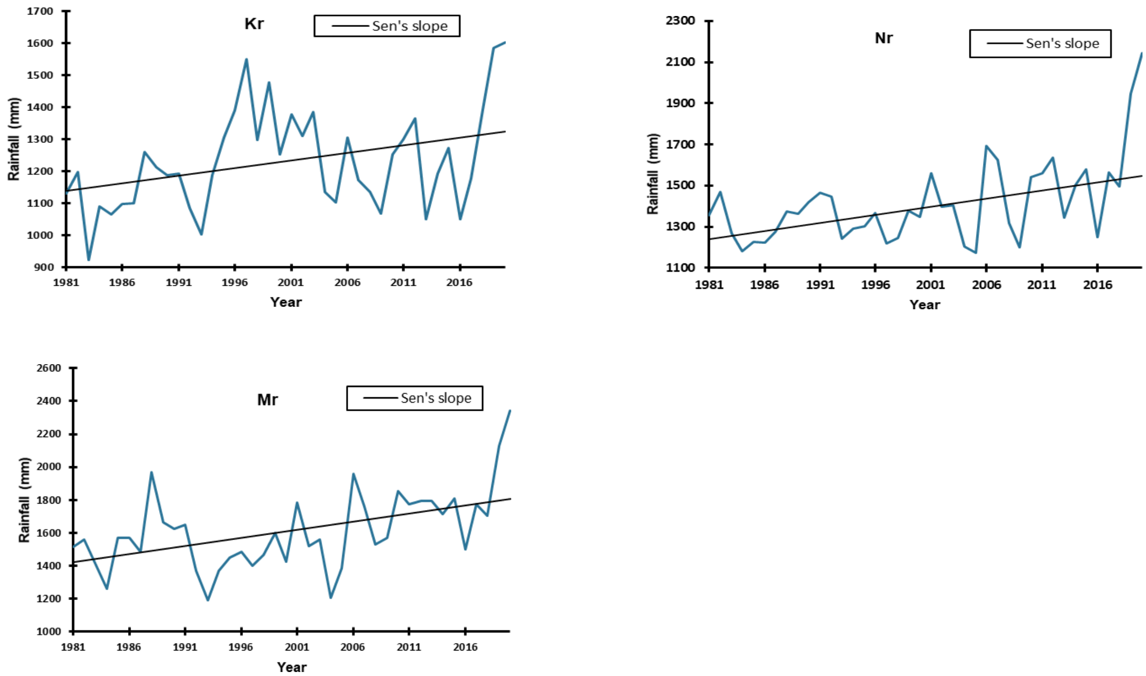


Figure 4.3: Trends in annual rainfall in Kampala (Kr), Mbale (Mr), Namutumba (Nr) Districts.

4.2.4 Estimation of windspeed trends

There is a significant variation in the windspeed over the 40 years (1981 to 2020) in Kampala ($p<$ 0.0001) and Namutumba Districts (p=0.002) with increasing speed respectively, by as little 0.005 m $^{s-1}$ and by 0.003 m $^{s-1}$ yearly **(Table 4.3, Figure 4.4)**. In that order, higher windspeed increases insect movement. There was no significant variation in the windspeed in Mbale **(Table 4.3)**.

Table 4.3: Estimated Sen's Slope values for the windspeed trends from 1981 to 2020.

Location	**Range**		**Sen's Slope**	***p*-value**
	Minimum	Maximum		
Kampala	1.23	1.60	0.005	< 0.0001
Mbale	1.49	1.74	0	0.953
Namutumba	1.21	1.49	0.003	0.002

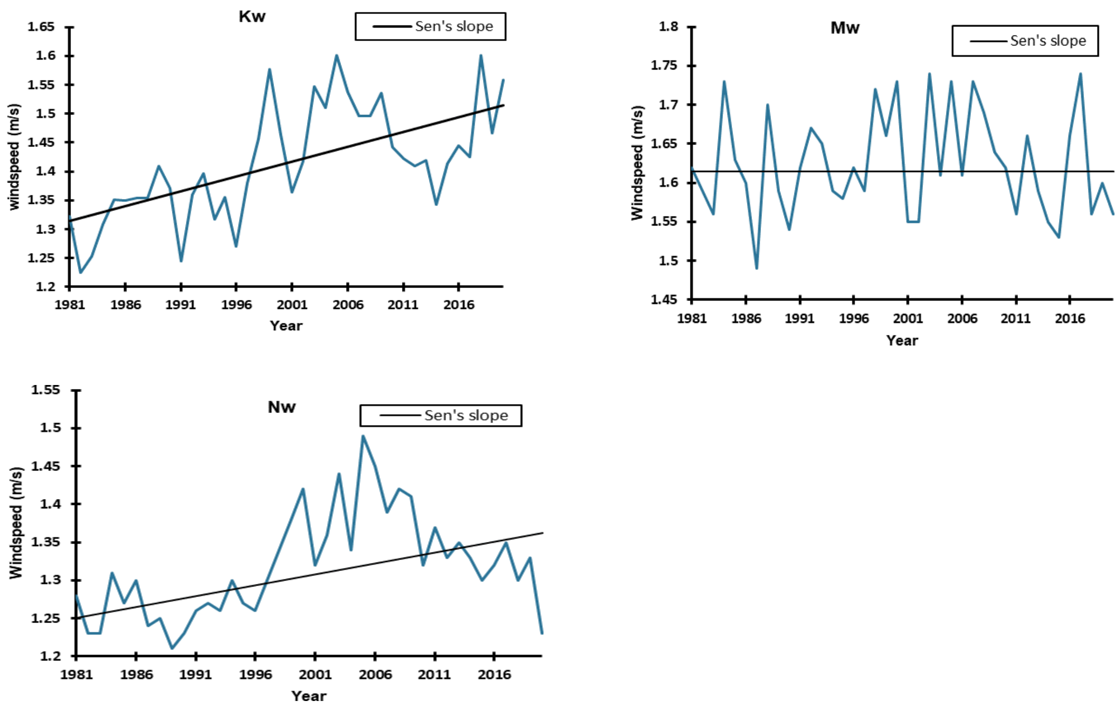


Figure 4.4: Trends in annual windspeed in Kampala (Kw), Mbale (Mw), Namutumba (Nw) Districts.

4.2.5 Estimation of trends in the humidity variable

MK and Sen's slope test showed variations in data with a significant decrease in the humidity over the years by 13.3% relative humidity (RH) in Kampala (*p*=0.001) and by 13.2% RH in Namutumba (*p*=0.035). In Mbale, there was no significance in the humidity trend (*p*=0.395). However, there was an increase in the humidity content over the years by 2% RH (**Table 4.4, Figure 4.5**).

Table 4.4: Estimated Sen’s slope values for the relative humidity trends from 1981 to 2020

Districts	**Range**		**Sen’s Slope**	***p*-value**
	Minimum	Maximum		
Kampala	69.03	79.91	-0.133	0.001
Mbale	72.06	84.38	0.025	0.395
Namutumba	59.88	80.31	-0.132	0.035

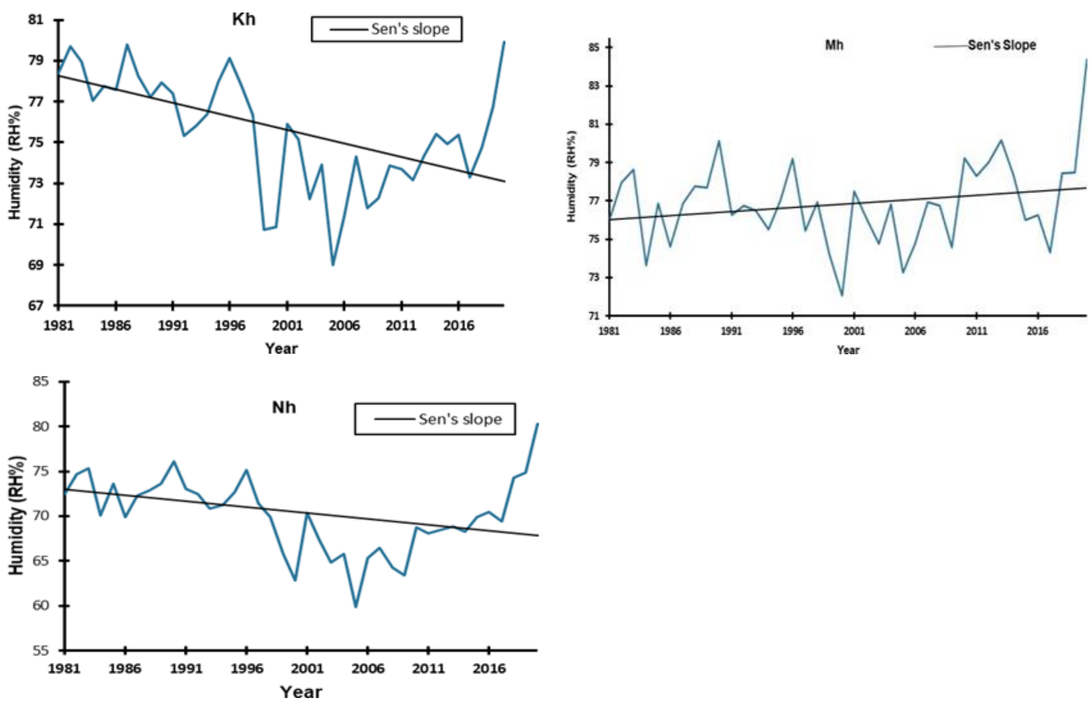


Figure 4.5: Trends in annual relative humidity in Kampala (Kh), Mbale (Mh), Namutumba (Nh) Districts.

4.2.6 Assessments of the relationships between climate variables and the occurrence of new insect pests in Kampala, Mbale and Namutumba

The results of the relationships between the occurrence of invasive tomato insect pests and windspeed, temperature, humidity, and rainfall were assessed by Pearson's correlation and were presented in **Figure 4.6**. There were negative relationships between the humidity variable and pest occurrence in Kampala and Namutumba Districts, as well as temperature variables, and pest occurrence in Mbale. The relationships among windspeed, temperature, rainfall variables and pest occurrence were positive in Kampala and Namutumba. The positive relationships observed in Mbale were among windspeed, humidity, and rainfall and pest occurrence. The associations among all studied climate variables and pest occurrence were significantly correlated ($p< 0.05$) in the three Districts, except for humidity in Kampala and windspeed, temperature, and humidity in Mbale.

The findings of the GLM analysis assessing the effect on pest occurrence of each climate variable are shown below **(Table 4.5)**. Due to over-dispersion with Poisson, we used the quasi-Poisson model. The GLM was fitted to the observed rainfall, temperature, humidity, windspeed, and the occurrence of invasive insect pests in Kampala. Air temperature (χ^2 = 31.331, df=1, p= 2.176^{e-08}), relative humidity (χ^2 = 12.23, df=1, p= 0.0005), rainfall (χ^2 = 8.4699, df=1, p=0.004) and wind component (χ^2 = 28.868, df=1, p= 7.749^{e-08}) at various pressure levels were all significant in the occurrence model. Rainfall, temperature, and windspeed positively affected pest occurrence counts while relative humidity affected the occurrence negatively. In the Kampala agro-ecological system where all the climatic variables interact together, windspeed ($p<3.45^{e-12}$) is much more significant in pest occurrence than rainfall ($p<2.06^{e-11}$) followed by temperature ($p<1.60^{e-08}$). The variations simultaneously in both windspeed and relative humidity are the major effect of the pest occurrence ($p=4.87^{e-12}$). The concurrent variations in all the variables are likely to have a low effect on the pest occurrence (p= 0.054) as shown in **Table 4.5**.

The significance of climate variables in Mbale on the occurrence of pest counts varied in the model (**Table 4.5**). Significant differences in occurrence were only observed in rainfall (χ^2 = 11.877, df=1, p= 0.0007). On the contrary, there was no significant influence on temperature (χ^2 = 0.38599, df=1, p= 0.5344) windspeed (χ^2 = 0.074178, df=1, p= 0.78) and relative humidity (χ^2 = 1.4828, df=1, p= 0.23) on the invasive insect pests counts. In this case, rainfall is the only parameter that (p= 0.0017) affects the invasive insect pest occurrence when the variables are combined in one model. The variations in relative humidity, windspeed, and rainfall ($p = 0.028$) as well as the variations in relative humidity, windspeed, and temperature ($p = 0.027$) are the only cases of significant change in the pest occurrence.

The effects of climatic variables on invasive insect pests in Namutumba have similar results in Kampala. Their shared trends could explain this similarity and effect **(Table 4.5)**. Similar to Kampala, rainfall in Namutumba had a significant effect on the pest ($\chi^2 = 12.893$, df = 1, p= 0.0003). Among other variables, the temperature did influence pest occurrence ($\chi^2 = 3.8541$, df=1, p

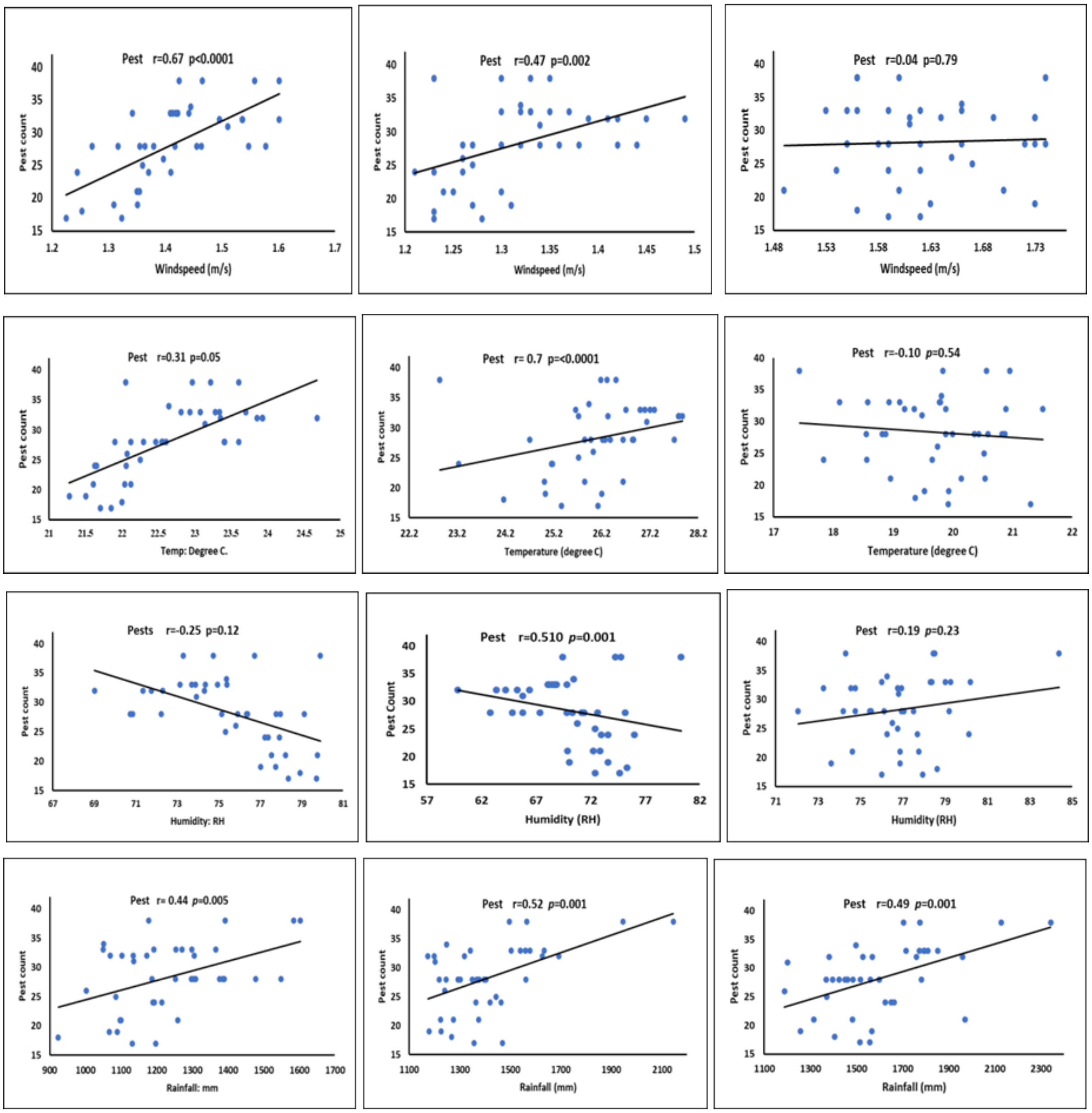
= 0.04962) as well as windspeed ($\chi^2 = 9.7638$, df = 1, $p = 0.00178$) compare to relative humidity which had no significant influence pest occurrence ($\chi^2 = 2.4605$, df=1, $p = 0.1167$). The new occurrence of invasive insect pests in the Namutumba agro-ecological system where all the climate variables interact together is highly influenced respectively by windspeed ($p = 7.612^{e-06}$), rainfall ($p = 0.002$), humidity ($p = 0.04$) (**Table 4.5**). Similarly, the interaction between windspeed and rainfall significantly affects the probability of new pest invasion ($p = 0.021$).

Table 4.5: Generalized Linear Model terms for estimating pest count, as a function of climate variables, of the three Districts (Dis): Kampala (K), Mbale (M), Namutumba (N)

Dis.		**Rainfall**	**Temperature**	**Humidity**	**Ws**
K	LR Chisq	8.4699	31.331	12.23	28.868
	Df	1	1	1	1
	Pr(>Chisq)	0.004	2.176^{e-08}	0.0005	7.749^{e-08}
M	LR Chisq	11.877	0.38599	1.4828	0.074178
	Df	1	1	1	1
	Pr(>Chisq)	0.0007	0.5344	0.23	0.7853
N	LR Chisq	12.893	3.8541	2.4605	9.7638
	Df	1	1	1	1
	Pr(>Chisq)	0.0003	0.04962	0.1167	0.00178

	Rh	Ws	Rf	T	Rh* Ws	Rh* Rf	Ws* Rf	Rh* T	W* T	Rf* T	Rh * RF* Ws	T* Ws* Rh	Rh* Rf *T	Ws* Rf *T	Rf* T* Ws* Rh
K	1.07^{e-15} *	3.45^{e-12} *	2.06^{e-05} *	1.60^{e-08} *	4.87^{e-12} *	0.03 *	0.6	0.01*	0.35	0.89	0.19	0.22	0.59	0.02 *	0.054.
M	0.17	0.25	0.0017 *	0.34	0.84	0.90	0.22	0.62	0.81	0.85	0.028 *	0.027*	0.13	0.78	0.75
N	0.04 *	7.612^{e-06} *	0.002 *	0.32	0.28	0.29	0.021 *	0.19	0.4	0.7	0.95	0.22	0.97	0.83	0.78

Significance: *$p<0.05$. Relative humidity: Rh; windspeed: Ws; rainfall: Rf; temperature: T



Kampala **Namutumba** **Mbale**

Figure 4.6: Pearson's correlation analysis of associations between climate variables and the occurrence of tomato invasive insect pests; r is the correlation coefficient.

4.2.7 Discussion

Evidence on climate trends and their effect on insect pests in Uganda, specifically in Kampala as the starting point, Mbale and Namutumba, the cultivated tomato areas, are explained. Our results showed an increasing annual temperature trend in Kampala and Namutumba and some abnormalities in Mbale over the last 40 years by 0.04^{o}C. Similar to Alemu and Doha (2020), there was a demonstration in increase in temperature in Uganda, namely; in Kampala, and Namutumba and the resulting humid and warm climate, favours pests' rapid growth and proliferation (Chivian, 2000). The cooling of temperature from 2008 to 2015 could be explained by natural variability.

The research showed that the rainfall trends increased significantly in Kampala (0.24 mm/year) and Mbale (0.0011mm/year), with a significant decrease in the humidity in Kampala and Namutumba, confirming the conclusions of Ssentongo *et al*. (2018). They stated a decrease in rainfall in Uganda of around 12% during the past thirty-four years (1983-2016) in Uganda. The trends of windspeed amplified between 1981 and 2020; our data show an increased rate of 0.05 m $^{s-1}$ and 0.003 m $^{s-1}$, in Kampala and Namutumba during the study period. The rise of invasive insect pests in Uganda is wind-aided due to the positive relationship between the wind and pest data. This validates previous assumptions that strong winds favour the migration of some pests, which propel them (Nurzannah *et al.*, 2020; Salih et al., 2020; Wainwright *et al.*, 2020).

The abnormalities in the annual precipitation trends are evidence of unpredictable rainfall patterns in the study area. Therefore, it is evident that rainfall has a significant positive relationship with pests (Nduru and Huho, 2018). The increase in rainfall in these historical data indicated moments of flood seasons. Additionally, the analysis of rainfall variability in Uganda has proven that extreme events such as floods and mainly droughts distorted tomato productivity through diseases and insect pests, calling for adaptive measures to help farmers (Malyse, 2020). The increase in humidity and temperature is beneficial to pest establishment in some locations (Shamshiri *et al.*, 2018; Zheng *et al.*, 2020). The opposite creates a favorable environment for increasing some pest populations, as confirmed by our study in Mbale. A study done by Khan (2019) showed that the population of aphids had increased from 2.12 to 2.35 after seven days under unsprayed conditions when relative humidity shifted from 61 to 50%, which confirmed the findings in Mbale and Namutumba, where the humidity has decreased with an increase in pests.

Overall, the occurrence of pest establishment trend increased. The fluctuations in the temperature and windspeed variables are associated with the rise of pests. This gives meaning in the association between increasing pests and climate variables. The findings of this research are comparable to those described by Huang *et al*. (2011). They discovered a positive impact of temperature on the increase in exotic insects' establishment rate in the United Kingdom, the United States, and China. Likewise, the outcomes consider preceding outcomes from a study by Phophi *et al.* (2020). They concluded that changes in climate become the crucial factor influencing pest outbreaks and invasion in the Limpopo Province of South Africa. Scientific studies from The International Centre of Insect Physiology and Ecology (ICIPE) and the Centre for Agriculture and Bioscience International (CABI) support that climate change is a major driver of transboundary pests' establishment in Eastern Africa. Besides, rainfall and temperature variability are susceptible to influencing pests' occurrence while affecting tomato production (Bisbis *et al.,* 2018; Nduru and Huho, 2018). Invasive pests such as leaf miners and thrips influence tomato yield loss and quality (Call and Gray, 2020; Gabriel, 2021; Taylor *et al.,* 2018). While the climatic conditions seemed favorable, the breakout of insect pests could have negatively impacted tomato production.

Moreover, the Generalized Linear Model with quasi-Poisson results showed significant relationships between climate variables and pests. Despite the fact that the causes of biological invasions are numerous and multifaceted, changes in the abiotic and/or biotic components of the environment (climate change, biological control) are recognized as primary drivers of species invasion (Kambrekar *et al.*, 2016). The remaining pest variation that the model could not capture as a function of climatic variables could be explained by other factors such as trade and cultivar exchange. Overall, extremely high temperatures, changes in rainfall and windspeed patterns increase the risk of introducing invasive insect species with an expansion of their geographic range (Skendžić *et al.*, 2021).

Finally, the current study made use of secondary data and promotes the movement of open data science, data sharing, and re-use in order to answer future research questions. This study suggests that the increase in invasive insect pest establishment rates in Uganda over the last four decades can be explained in part by climate change, given that temperature, rainfall, windspeed, and humidity facilitate bio-invasion.

4.2.8 Summary

The study's first objective was to determine the effect of climate change on the occurrence of tomato invasive insect pests. The study found changes in the climate variables, temperature, windspeed, rainfall and relative humidity in Kampala, Namutumba and Mbale from 1981 to 2020. Also, there was a discovery of an increase in the occurrence of new invasive tomato insect pests from 1981 to 2020. These climatic changes in those Districts explained the perpetual invasion of new pests. These changes put at risk the smallholders' farmers' crop production. Due to this drastic situation, the farmers are adopting climate-smart pest management technologies and practices to adapt to the impact of climate change.

4.3 Opportunities and challenges associated with conventional adaptation strategies and CSPM technologies.

This objective was addressed by data collected in both Mbale and Namutumba Districts. The study's second objective sought to find the opportunities and challenges encountered by smallholder farmers in adopting CSPM technologies. Some of the CSPM technologies that were in place during the study were parasitoids, push pull, biopesticides, and plant extracts. From the findings, 50.2% (majority) were from Mbale District, while 49.8% were from Namutumba District.

4.3.1 Socio-demographic characteristics

This section sought to find out the social and demographic characteristics of the sampled smallholders' farmers in Mbale and Namutumba districts. Several variables were investigated. These included respondents' demographic characteristics, such as, gender, age, head of household, educational level. **Table 4.6** summarized the findings.

Table 4.6: Socio-demographic characteristics of the sampled farmers in Mbale and Namutumba Districts, Uganda.

Socio-demographic characteristics	**Districts**				Total (N)
	Mbale		Namutumba		
		Freq.		**Freq.**	
Gender	Male	86	Male	90	176
	Female	120	Female	114	234
	Total	206	Total	204	410
Age	B. 25 Ys	10	B. 25 Ys	14	24
	26-40 Ys	130	26-40 Ys	70	200
	41-55 Ys	43	41-55 Ys	80	123
	O. 56 Ys	40	O. 56 Ys	22	62
Household headed	Male	129	Male	111	240
	Female	100	Female	70	170
	Total	229	Total	181	410
Education	Pre-primary/none	100	Pre-primary/none	129	229
	primary	73	primary	50	123
	R. education	38	R. education	20	58
	total	211	total	199	410

NB: Freq: Frequency

The majority of the findings (120) and (114) indicated that they were females respectively from both Districts of Mbale and Namutumba, while 90 and 86 of the respondents were male. This demonstrates gender was well represented in our study. Furthermore, based on percentages, male and female smallholder farmers were nearly equally represented. Regarding age, the majority of the respondents in Mbale, 130, were aged between 26-40 years. Further, the study revealed that 80 of the respondents in Namutumba were aged between 41-55 years.

Regarding household heads, from 229 respondents in Mbale District, only 100 of households were female-led. The remaining 129 of households were male-led. In Namutumba District, there were

181 respondents, of which 70 households were female-led while 110 were male-led. Regarding education, with a pre-primary level of education, 129 were from Namutumba, while 100 were from Mbale. Regarding primary education, there were 123 respondents where 73 were from Mbale, and 50 were from Namutumba. Finally, there were 57 respondents on religious education; 38 were from Mbale, while 20 were from Namutumba Districts. This demonstrates that, on average, farmers may have only the bare minimum of education required to comprehend agricultural instructions about climate-smart pest management technologies.

Land ownership

Smallholder farmers and those who farm on leased land are unlikely to implement major climate adaptation approaches (Njuguna *et al.*, 2019). Land ownership, therefore, is associated with the ability to uptake CSPM. It is then important to establish land crop production, as expressed in **Table 4.7**.

Table 4.7: Land ownership

Land ownership	**Gender**			
	Female (N=253)	**Male (N=157)**	**Total (N=410)**	***p* value**
Yes	250	148	398	0.03[1]
No	3	9	12	<0.01[1]

From the findings, 250 of females and 148 of males indicated that they have access to land for farming, while 3 of females and 9 of males were of the contrary opinion. This suggests that smallholder farmers will have no difficulty adopting the CSPM in this regard.

4.3.2 Knowledge and perception of farmers about climate change

Farmers' perceptions about the changes in the climatic patterns was assessed along with the occurrence of invasive insect pests. Farmers were asked if they had noticed any changes in temperature and rainfall patterns in the preceding 25 to 35 years. Findings from **Table 4.8 and Figure 4.7**

Table 4.8: Perception of farmers about changes observed in the rainfall, temperature patterns from the past 35 years (1985-2020).

Climatic parameters	Observation on changes in climatic parameters	Frequency
Rainfall amount	Decrease	226
	Increased	184
Temperature	Decreased	172
	Increased	238

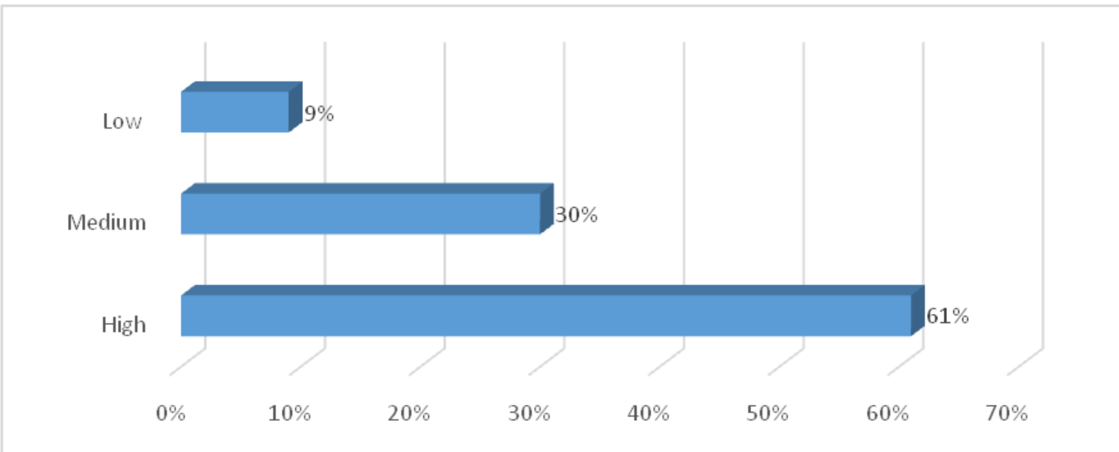


Figure 4.7: Perception of farmers on the occurrence of the invasive insect pests

Most respondents indicated the rainfall amount has slightly decreased 226 while temperature 238 has increased over the past 35 years. In addition, 61% of the respondents reported a high invasion of tomato invasive pests; 30% indicated the occurrence level was medium, while 9% indicated low. The farmers reported that the weather was becoming drier yearly with the proliferation of many crop diseases and pests (**Figure 4.7**). According to them, these climatic

changes have affected their yield and food production leading to food price increases. Climate induced pests had a significant impact on the respondent's livelihoods.

4.3.3 Consultation on control and management of crop pests

The study went on to establish the consultation entity for crop pest control and management. **Table 4.9** summarized the findings.

Table 4.9: Consultation on control and management of crop pests

Consultation on Control and Management of Crop Pests	Percentage
Ministry of Agriculture (Extension officer)	20%
Village committee	34%
Farmers organization	58%
Local political leaders	7%
Support organization (Food for the Hungry)	45%
Neighbour/friend	38%

The majority of respondents (58%) rely on farmer's organizations to control and manage crop pests, while 45% rely on support organizations. The least was the local political leaders (7%), followed by the Ministry of Agriculture (20%) in ascending order.

4.3.4 Gender involvement

4.3.4.1 Personnel monitoring of pests

Monitoring is an essential CSPM practice which involves action to reduce crop destruction. Therefore, the level of implication in monitoring is important to ensure the proper deployment of CSPM, as illustrated in **Figure 4.8**.

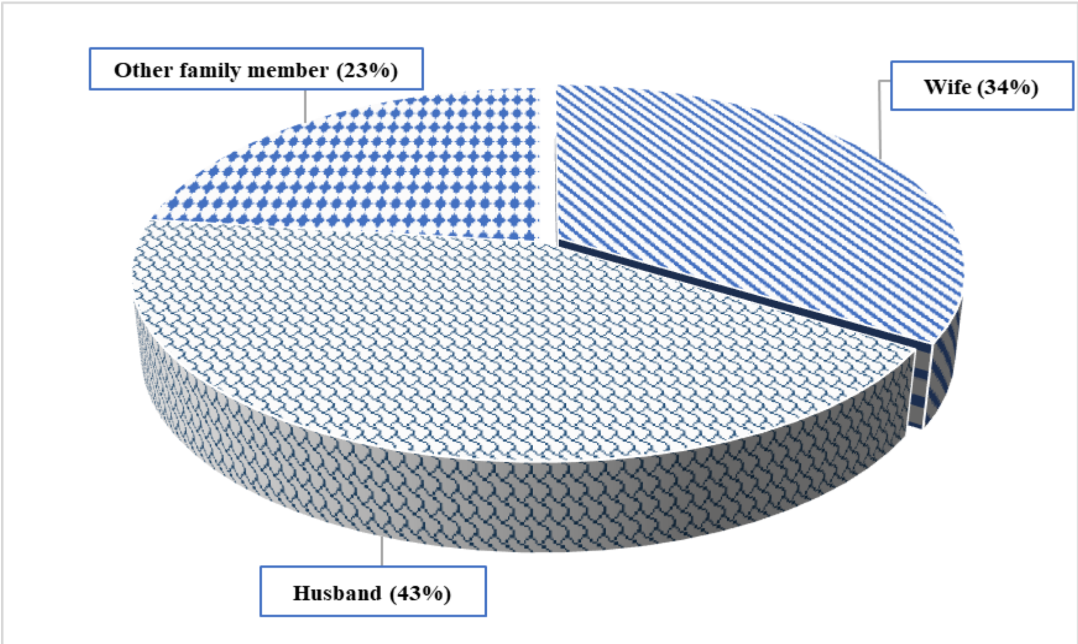


Figure 4.8: Personnel monitoring of pests

43% of the respondents specified that the husband was the one in charge of monitoring pests, 34% indicated the wife, while the remaining 23% indicated other family members like children, relatives. It still showed the strong impact of male in decision making of pest control even for those households headed by females.

4.3.4.2 Entity in charge of pest control

Figure 4.9 provides the importance of gender in pest control.

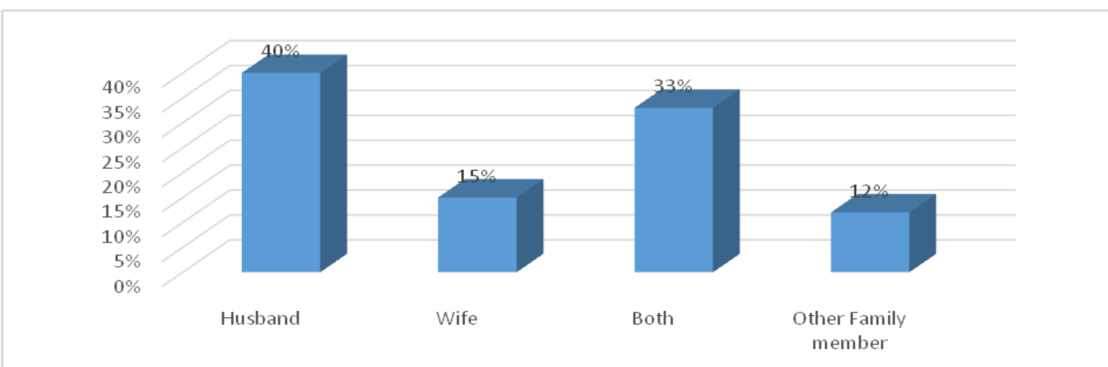


Figure 4.9: Entity in charge on pest control

NB: Both are considered to be decisions is made by common agreement between husband and wife; other family members are either children or relatives.

According to the findings (40%), the husband is in charge of pest control, 33% indicated both husband and wife, 15% indicated wife, and 12% indicated other family members. Namely, it is an indication that women who had access to land farming were not directly in charge of the decision to control pests or the method used to control them. Thus, a clear barrier to the adoption of CSPM.

4.3.5 Practices of pest control

The respondents were requested to indicate how they rank the various pest control practices. The ranking scale was from 1 to 5. The findings are shown in the **Table 4.10**.

Table 4.10: Ranking of practices for pest control

Practice	**Rank**
Monitoring	3.698
Push Pull	3.437
Organic Pesticide	3.322
Crop Rotation	3.202
Hand Pulling	3.122
Destroying Infected Plants	3.076
Mulching	2.805
Cow Urine	2.617
Chemical Pesticides	2.524
Bio-Pesticide	1.256
Trap	0.615
Parasitoids	0.217
Screen house	0.215

From the findings, monitoring was ranked the highest with a score of 3.698 followed by Push Pull, which received 3.437 score. Additionally, the respondents ranked the trap the lowest with a score of 0.615, followed by parasitoid and screen house scoring 0.217, and 0.215 in an ascending order.

4.3.6 Institutional factors

The study sought to identify the institutional factors influencing CSPM upscaling among sampled farmers in both Districts. These were knowledge of CSPM technologies and practices, use of CSPM, extension services, and farmers' association.

4.3.6.1 Knowledge, awareness and use of CSPM

Knowledge management in climate-smart pest management technologies plays an important role in Uganda's National Climate Change Action Plan. This study assessed the respondents' extent of knowledge and awareness of CSPM technologies that help them adapt to climate change.

Table 4.11 displayed the results.

Table 4.11: Awareness and use of CSPM based on gender of the respondents.

Knowledge/awareness about CSPM	Female	Male	Total
	Frequency		
Yes	150	120	270
NO	84	56	140
Use of CSPM			
Yes	148	106	254
No	86	70	156

From the findings, about 270 of the respondents were aware of CSPM technologies or non-pesticide pest control, while the remaining 140 were unaware. This implies that CSPM adoption may be difficult, necessitating the establishment of structures that allow information to reach as many farmers as possible. Therefore, further information was sought on the use of CSPM. Findings in **Table 4.11** shows that only 254 of households use any CSPM, while the remaining 156 do not.

4.3.6.2 Farmer associations

Each farmer association is goal-oriented. For example, Magada United Rice Farmers Cooperation is supporting in many ways a variety of crop production. Also, when a farmer belongs to any particular association, the chances to come into contact with CSPM practices and technologies are high. Findings in **Table 4.12.**

Table 4.12: Farmer's association

Farmer's Association	Frequency	Percentage
Yes	295	72%
No	115	28%

Majority of the farmers interviewed (72%), indicated that they were members of farmer's association while 28% were not.

4.3.6.3 Access and main provider of extension service

Extension officers are the official delegates of the government. Their role is to disseminate the information and agricultural practices to farmers at the grassroots level. Their services play an important role in the adoption, dissemination and upscaling of CSPM practices and technologies. It is therefore important to determine whether the farmers have gotten any support from the Ministry of Agriculture extension officers or the non-governmental organisations, as illustrated in **Table 4.13**.

Table 4.13: Access to extension service

Respondents access to extension Service	Female (N=214)	Male (N=196)	Total
No	185	163	348
Yes	29	33	62

From the findings in Table 4.13, about 348 of respondents indicated that they have not received from extension officers any substantial information about CSPM within the last 12 months of the research, while 62 received some information. This challenge could be because farmers, most of the time, seek information from the offices of the extension workers, which are quite distant from their homes. Also, another reason is that in both Districts, one could only find one or two extension officers allocated or dedicated to their tasks.

Despite this challenge, farmers recognised that the information they got about the CSPM was given mostly by farmer's associations and NGOs such as Food for the Hungry **(Table 4.9)**.

4.3.7 Opportunities for using climate smart pest management technologies and practices to control tomato invasive insect pests in the face of climate change by farmers.

Farmers have used several approaches to deal with pests. However, with the increasing invasion of new insect pests, climate-smart pest management practices and technologies are slowly being adopted by farmers to overcome the effects of climate change. Therefore, the study sought to establish the positive gains associated with upscaling CSPM. The results of the analyses on the opportunities associated with CSPM are presented in **Table 4.14.**

Table 4.14: Analysis on opportunities associated with CSPM

Opportunities Associated with CSPM	Mean
CSPM contribute in pest reduction	3.782
Contribution of CSPM to the reduction of chemical pesticides use	3.670
CSPM strengthen farmers resilience to climate change	3.871
CSPM improve crop quality	3.902
CSPM contribute in lowering environmental pollution	3.564

From the findings, the respondents indicated that CSPM improves crop quality (mean = 3.902); strengthens farmer's resilience (mean = 3.871); leads to pest reduction (mean = 3.782); contributes to the reduction of chemical pesticides use (mean = 3.67), and; contributes to lowering environmental pollution (mean = 3.564).

Factor analysis of the opportunities associated with CSPM

Factor analysis was conducted to reduce the dimensions of factors (opportunities) and give insights into opportunities considered when making operational decisions concerning CSPM. This was important to help identify the opportunities related to the implementation of CSPM. **Table 4.15** shows the proportion of each variable's variance explained by the factors (communalities).

Table 4.15: Communalities on opportunities

Opportunities for CSPM	Initial	Extraction
1- CSPM reduces chemical pesticides use	1.000	0.961
2- CSPM improve crop quality	1.000	0.943
3- CSPM contribute in lowering environmental pollution	1.000	0.940
4- CSPM strengthen farmers resilience	1.000	0.912
5- CSPM helps in pest reduction	1.000	0.887

The study sought the key opportunities that arise from using CSPM. It was discovered that the majority of the factors had extraction variances greater than 0.7. The highest extraction opportunities were CSPM reduces chemical pesticides use with 0.961, followed by CSPM improves crop quality with 0.943, and CSPM contributes to lowering environmental pollution with 0.940. A method of extraction of factor analysis was used to measure variable importance in **Table 4.16.**

Table 4.16: Contribution of extracted variable on opportunities

Total Variance Explained						
Comp	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% Variance	Cumul %	Total	% Variance	Cumul %
1	15.894	31.788	31.788	15.894	31.788	31.788
2	4.912	9.824	41.612	4.912	9.824	41.612
3	4.233	8.467	50.079	4.233	8.467	50.079
4	-1.023E-013	-1.045E-013	100.000			
5	-1.029E-013	-1.058E-013	100.000			

NB : Cumul - Cumulative ; Comp - components

Three major components were extracted (**Table 4.16).** The first three components of importance have Eigenvalue greater than 2.1. Together they explain about 50.08% of the total variability of the data. As a result, the three components are likely sufficient for making significant operational decisions regarding the implementation of CSPM technology. The three keys extracted components include: CSPM reduces chemical pesticide use (1); CSPM improve crop quality (2), and CSPM contributes to lowering environmental pollution (3) **(Table 4.16).**

4.3.8 Challenges faced by farmers to adoption of climate smart pest management technologies and practices.

Data was analysed using factor analysis to identify the barriers or challenges associated with conventional adaptation strategies and CSPM technologies, as well as the most important factors to be considered during decision-making when adopting CSPM technology. **Table 4.17** showed the results.

Table 4.17: Communalities on challenges

Challenges on use of CSPM	Initial	Extraction
1- Limited national and local government support for the adoption of CSPM technologies	1.000	0.975
2- Cultural beliefs on the adoption of CSPM	1.000	0.924
3- Limited training on the handling of any CSPM	1.000	0.897
4- Gender issue on the adoption of CSPM	1.000	0.883
5- Costly CSPM technology such as screen house/push-pull seeds	1.000	0.840
6- Limited affordability to any CSPM technologies	1.000	0.837
7- Inadequate access to appropriate CSPM handling tools	1.000	0.829
8- Limited access to farming land	1.000	0.828
9- Limited enough facilities for storing, and protecting CSPM from theft	1.000	0.778

As per **Table 4.17**, the majority of challenges had an extraction of more than 0.7 proportion of variance. The most significant extraction factor was the limited national and local government support for adopting CSPM technologies with 0.975, followed by cultural beliefs on the adoption of CSPM with 0.924. Also, limited training on the handling of CSPM had 0.897; gender issue on the adoption of CSPM with 0.883; cost of CSPM technology such as screen house/push-pull seeds with 0.84; lack of affordability to any CSPM technologies with 0.837; inadequate access to appropriate CSPM handling tools with 0.829; limited access to farming land with 0.828, and lack of enough facilities for storing, protecting CSPM from theft at 0.778. A method of extraction of factor analysis was used to measure variable importance in the challenges of CSPM adoption, and the results are given in **Table 4.18**.

Table 4.18: Contribution of extracted variable on challenges

Comp	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumul %	Total	% of Variance	Cumul %
1	16.333	40.832	40.832	16.333	40.832	40.832
2	4.660	11.651	52.483	4.660	11.651	52.483
3	3.428	8.571	61.054	3.428	8.571	61.054
4	2.755	6.887	67.941	2.755	6.887	67.941
5	1.780	4.451	72.392	1.780	4.451	72.392
6	.921	2.303	88.447			
7	.783	1.958	90.405			
8	3.064^{E-018}	$7.660E^{-018}$	100.000			
9	-1.018^{E-017}	-2.546^{E-017}	100.000			

NB : Cumul - Cumulative ; Comp - components

From **Table 4.18,** the components with an Eigenvalue greater than 2.5 are the first four components. The four components account for 67.941% of the total data variability. The four components are most likely sufficient for making significant decisions concerning the key barriers in the upscale of CSPM. The key extracted components with the highest extraction value which includes: limited national and local government support on the adoption of CSPM technologies (1), cultural beliefs on adoption of CSPM such as parasitoids, push pull (2), limited of training on the handling of any CSPM (3) and gender issue on adoption of CSPM (4) **(Table 4.18).**

4.3.9 Discussion

Adapting to climate change is a challenge faced by smallholder farmers in this present time. From the study, farmers have witnessed that climate-smart pest management technologies and practices have been very important to help them tackle invasive tomato pests like *Tuta absoluta* in their farms. Many benefits related to the adoption of CSPM are reducing chemical inputs in the farms, building farmers' resilience, lowering environmental pollution and increasing crop yield. Furthermore, it confirms that supporting integrated pest management technologies reduces the negative impacts of pesticides among integrated pest management (IPM) farmers (Mwungu *et al.*, 2020). The findings also agreed with recent studies in pest management, which acknowledged push-pull technology as efficient in controlling pests and improving soil fertility (Hailu *et al.*, 2018). Push-Pull is a cropping system that uses one organism to repel the pest that another organism attracts through the emission of semio-chemicals (Khan *et al.,* 2016). Though smallholder farmers in Namutumba and Mbale are adopting CSPM, its upscaling is low due to demographic, cultural, political and socio-economic barriers (Al-zyoud, 2015; James *et al.,* 2012). Recent studies by Niassy *et al.* (2022) bring out the challenges farmers face in upscaling push-pull CSPM in most African regions. Across Namutumba and Mbale, there were cultural beliefs and superstitions, a lack of serious involvement of farmers in decision-making about CSPM promotion and adoption, limited access to farmland and appropriate handling tools (certified seed, pheromones, parasitoids cages), high cost of the CSPM, lack of adequate physical and social infrastructures such as roads, markets, and storage facilities. More resilient and sustainable pest management practices are needed to reduce crop yield loss due to pest activity and to mitigate the negative effects of pest management on human health and the environment (Baker et al., 2020). All these challenges are important in making operational decisions that help improve the farming practices about technology.

4.3.10 Summary

The study's second objective was to determine opportunities and challenges related with CSPM adaptation strategies. According to our respondents, CSPM technologies and practices have contributed to the adaptation of climate change effects on their crop production, mostly their tomato farms. Among the opportunities recorded by farmers, we have reduced chemical use, decreased pest density in their farms, and improved crop yield while lowering the environmental pollution. However, some challenges are confronted by upscaling of these CSPM technologies and practices. Key barriers to these challenges are cultural beliefs, lack of strong publicity from the national government in adopting CSPM, and the lack of good infrastructures such as roads and good markets. Therefore, there is a need for strong sensitisation on the importance of these climate-smart pest management technologies. The best method could be the use of digital tools. All these challenges are important in making operational decisions that help improve the farming practices in relation to technology.

4.4 Role of digital tools in the implementation of CSPM

The third objective of the study was to determine the role of digital tools in CSPM implementation. Digital technology is an influential domain that has been used to help farmers adopt CSPM and build their resilience in the face of climate change.

4.4.1 Owning of digital tools

The respondents were asked whether they own a mobile phone. The results are as presented in **Table 4.19**.

Table 4.19: Owning of digital tools

Type of digital tool	Owning and using	Frequency
Mobile phone	Yes	298
	No	112
Television	Yes	14
	No	396
Radio	Yes	243
	No	167
CD/DVDs, Laptop	Yes	6
	No	404

From the study findings, most of the surveyed farmers own a phone (298), and 243 also own a radio. This suggests that mobile phones and radio are the digital tools used by farmers to access information compared to TV (14), CD/DVDs and Laptops (6). However, the study reveals that the mobile phones owned by farmers were mostly not smartphones.

4.4.2 Perception of use of digital tools

This section intends to establish the use of the digital technologies in the uptake of information on crop cultural practices, crop pest outbreaks, spraying of chemicals, CSPM practices/ technologies, weather information, access to seeds, crop credit access, harvest and post-harvest methods, and market/selling prices. The data was obtained through the rating of use of each of these digital tools to acquire the information with 1 being less used and 5 being highest use.

The findings presented in **Table 4.20** revealed that radio was highly used to acquire information on CSPM practices and technologies and information on crop pest outbreaks. The findings noted that the respondents did not rate TV broadcasts, social media, CD/DVDs and flash disks as modes of acquiring various information concerning crop and pest management.

Table 4.20: Use of digital tools

	Crops Cultural practices	Crop Pest outbreaks	Spraying of chemicals	CSPM practices / Technologies	Weather information	Access to seeds	Crop Credit access	Harvest and post-harvest method	Market/selling prices
Phone	1.127	1.068	0.812	1.293	0.780	1.051	0.685	0.998	1.149
Tv broadcast	0.266	0.234	0.205	0.224	0.251	0.17 8	0.127	0.217	0.215
Radio	1.688	1.698	1.510	1.556	1.683	1.41 5	1.012	1.598	1.673
Social media	0.117	0.107	0.085	0.088	0.102	0.07 1	0.056	0.107	0.073
CD, DVDs, flash disks	0.039	0.027	0.022	0.032	0.010	0.010	0.020	0.020	0.034

4.4.3 Relevance of information gotten through the digital tools

The respondents were asked to designate the relevance of the information they received on crop and pest control practices. The results are given in **Table 4.21**.

The study gathered information to find out from the farmers how relevant the information they received through the digital tools. It is an indicator of the way forward on the possibilities of using digital tools to help uptake CSPM. It was revealed, according to the farmers, that information on CSPM practices/ technologies was relevant (mean = 3.383), followed by information on harvest and post-harvest methods (mean = 3.132), information on pest outbreaks (mean=2.995). In an informal interaction, some farmers indicated that some NGOs campaign on radios about how to use climate-sensitive practices on their farms.

Table 4.21: Relevance of agricultural information to farmers

Relevance of Information	Mean
Information on Crops Cultural practices	2.798
Information on Pest outbreaks	2.995
Information on Spraying of chemicals	2.644
Information on CSPM practices/ technologies	3.383
Information on Weather information	2.715
Information on Access to seeds	2.871
Information on Credit access	2.141
Information on Harvest and post-harvest method	3.132
Information on Market/selling prices	2.861

4.4.4 Farmers perceptions about the importance of digital tools in the upscaling of CSPM

Whether or not they agree with the statement, ‘farmers are no longer able to adopt and implement CSPM without digital technological services, a majority of respondents (about 56%) agreed with the statement as shown **in Figure 4.10** giving the following reasons: increase in production; weather information being accurate and timely compared with their guesswork about whether previously; crops cultural practices, crop pest outbreaks, access to seeds, harvest and post-harvest method, market/selling prices, and many other reasons. It also lessens their burdens to reach the extension offices.

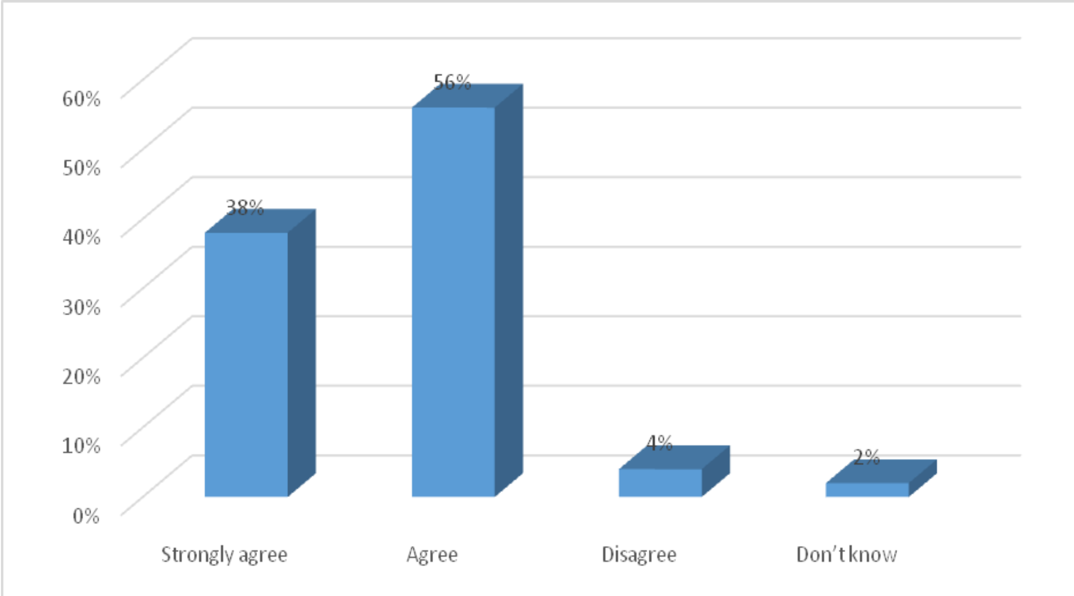


Figure 4.10: Importance of digital tools on control practices

4.4.5 Regression analysis between digital tools and CSPM implementation

The research used simple regression to find the association between the predictor variable and the implementation of CSPM. The independent variable in this study was digital tools, while the dependent variable was the implementation of CSPM.

4.4.5.1 Model Summary

Table 4.22 summarizes the model's relationship between the predictor variable and CSPM implementation. The outcomes are as specified in **Table 4.22.**

Table 4.22: Model validation of CSPM implementation

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	*p*-value
1	0.747	0.558	0.545	0.34309	0.001

a. Predictors: (Constant), Digital Tools
b. Dependent Variable: Implementation of CSPM

According to the findings in **Table 4.22**, the R^2 was 0.558, representing a 55.8% difference in implementing CSPM. As a result, the model's difference is explained by the independent variable.

Furthermore, the unexplained difference of 44.2% in the table is due to other factors not included in the model. As a result of the results in the table, it can be concluded that the model is suitable for estimation (sig value is less than 0.05).

4.4.5.2 ANOVA Results

Table 4.23 shows the ANOVA results of the relationship between the predictor variable and CSPM implementation.

Table 4.23: ANOVA of the regression

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	5.062	1	5.062	43.005	0.000[a]
	Residual	48.144	408	.118		
	Total	**53.206**	**409**			

a. Predictors: (Constant), Digital Tools
b. Dependent Variable: Implementation of CSPM

The significant value in **Table 4.23** was 0.000[a], which is significantly less than 0.05, indicating that the model was statistically significant. This illustrated how the model could be used to predict the relationship between digital tools and CSPM implementation. The model also discovered that the F critical (5.062) was less than the calculated F (value = 43.005), indicating that the model was statistically significant.

4.4.5.3 Coefficient of Determination

Table 4.24 provides the coefficient of determination on the relationship between the predictor variable and implementation of CSPM.

Table 4.24: Coefficient of determination

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	T	Sig.
Model 1(Constant)	0.349	0.573		0.610	0.546
Digital Tools	0.955	0.146	0.747	6.558	0.000

a. Dependent Variable: Implementation of CSPM

To determine the impact of digital tools on CSPM implementation, a simple regression analysis was performed. The following equation resulted:

$(\mathbf{Y = \alpha + \beta_1 X_1 + ẹ})$

Becomes:

$(\mathbf{Y = 0.349 + 0.955 + \varepsilon})$

The implementation of CSPM was 0.349 based on the regression with the independent variable (digital tools) constant at zero. The data showed that a unit increase in digital tools leads to a 0.955 increase in CSPM implementation. Digital tools were significant in implementing CSPM at a 5% level of significance and a 95% confidence level.

4.4.5.4 Correlation analysis

Pearson's correlation analysis was used to determine the relationship between digital tools and CSPM technology implementation. The results are shown in **Table 4.25** below.

Table 4.25: Correlation analysis between digital tools and implementation of CSPM technologies

		Digital tools	Implementation of CSPM technologies
Digital tools	Pearson Correlation	1	
	Sig. (2-tailed)	.	
	N	410	410
Implementation of CSPM technologies	Pearson Correlation	.719	1
	Sig. (2-tailed)	.004	.
	N	410	410
**. Correlation is significant at the 0.01 level (2-tailed).			

Source: Field Data (2022)

From the table, a strong positive R-Value of 0.719 was established between digital tools and the implementation of CSPM technologies. This implies a significant relationship between digital tools and the implementation of CSPM technologies.

4.4.6 Discussion

The third objective of the study was to assess the perception of smallholder farmers on the role of digital tools in the implementation of CSPM in battling tomato invasive insect pests. The study found the most relevant information on CSPM practices/ technologies. The findings agreed with those of Tambo *et al.* (2019) who stated that the use of ICT and radio in Uganda increased farmers' knowledge about tomato pest control and which had a positive impact on the adoption of CSPM technologies. However, the National Climate Change Adaptation Strategies rarely emphasize the importance of CSPM in the agenda to cope with these devastating impacts. The study further found that the respondents agreed that digital tools could help deal with tomato pests efficiently. Though most respondents seemed to have less access to agricultural information on the current and smart digital tools and platforms, they usually received information through gatherings.

From the results, at a 5% level of significance and 95% level of confidence, digital tools were significant in implementing CSPM. Studies by Pretty and Bharucha (2015) elaborated that Integrating digital tools in pest control has demonstrated efficiency in reducing pesticide use with a concomitant increase in crop yields. Experts from The International Potato Centre and partners in their fight against Potato Late Blight used integrated pest management through the combination of Farmer Field Schools and a participatory approach to ease the farmers' information, technology, and knowledge access (Ortiz *et al.*, 2019).

4.4.7 Summary

The third objective of the study was to determine the role of digital tools in implementing CSPM. In the 21st century, technology plays an important role in disseminating information in the agricultural sector. Digital tools are useful for monitoring insects, receiving news on weather forecasts, pest outbreaks, and easy management of insects on the farms. Therefore, access to digital services for sustainable pest control in the face of climate change requires the smallholder farmers to own digital tools like smartphones, smart television, flash disks and DVDs that contain relevant information. According to the respondents, mobile phones have been their main channel to access agricultural information. But their tools are not smartphones, limiting accessibility to the latest information. The study further found that the respondents agreed that digital tools could help one understand the CSPM technologies, share updates of their demos to the agricultural support team, and for many other services. Finally, the study discovered that digital tools were significant in CSPM implementation at a 5% level of significance and a 95% level of confidence. As a result, policymakers must work to make digital tools more affordable and accessible to smallholder farmers in Mbale and Namutumba.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion of the study

The study found changes in climatic variables, such as temperature, rainfall, windspeed, and relative humidity in Kampala, Mbale, and Namutumba between 1981 and 2020. There was a significant rise in the occurrence of tomato invasive insect pests in those Districts affected by climatic changes in the area of study. Pest occurrence was positively correlated with rainfall and windspeed in all three districts. Temperature had a positive association with pest occurrence in Kampala and Namutumba, but a negative one in Mbale. Also, a decrease in humidity increased pest occurrence in Kampala and Namutumba. These differences could be attributed to different agro-ecological systems with different climatic data. The occurrence of pests in those districts is detrimental to tomato production. It, therefore, contributes to the damage to tomato crop and yield loss putting at risk farmers' livelihoods. Our findings could be used to educate various stakeholders and policymakers about the effects of climate change on pest occurrence and the importance of pest control in order to seek sustainable ways to deal with invasive pests while protecting the environment in Uganda.

The research concluded that climate-smart pest management technologies could be positively critical to improving the sustainability of agricultural processes, resulting in increased farm productivity while reducing environmental impact. Climate change impacts on agriculture are driving researchers and policymakers to begin implementing various new agricultural pest control techniques in this era of global warming. Although there were some barriers to farmers easily adopting CSPM, such as financial constraints, policy issues, limited access to CSPM technologies, limited access to information, and CSPM technology handling methods, smallholder farmers in Mbale and Namutumba were eager to embrace CSPM technologies with the aid of digital tools.

Therefore, smallholder farmers' capacity needs to be improved to overcome these challenges. For that matter, the majority of smallholder farmers agreed that in this 21st century, the use of digital tools can enhance their adoption of CSPM and hence the upscaling of these climate-smart pest management technologies. Digital tools will improve the upscaling of CSPM technologies that efficiently control tomato pests such as *Tuta absoluta.*

5.2 Recommendations and implications of the study

Based on the study found, the following recommendations are made:

- First, the suitability of technologies (parasitoids, push pull, screenhouses, biopesticides) in the studied area must be assessed in light of costs, farm size, and population cultural beliefs. Farmers would also benefit from increased awareness of the advantages of certain technologies and practices, as well as training in technology use.
- The establishment of co-production of knowledge setups whereby farmers and local experts can share knowledge and reinforce their practices should be promoted via social and digital platforms.
- There is an urgent need to improve extension systems. The study areas would benefit if the implementation of certain practices were conducted, such as, farmer field schools, and if the formation of farmers' groups was encouraged.
- More along the same lines, extension services must be strengthened. CSPM technologies and practices could be improved and spread more widely in the study areas, and farmer groups could be encouraged to form.
- Further, farmers could also stand a chance to be linked conveniently with extension service providers and farm financing agents. The government and development partners should invest in important infrastructure like electricity and roads, which could spur rural-based economic activities, making it easier for farmers to engage in off-farm income-generating activities.
- Farmers should be encouraged to join and participate in farmer organizations to share farming information in order to increase demand for CSPM technologies. As a result, the government and partners should invest in critical infrastructures and digitalization of pest control, which could stimulate rural-based climate economic tomato production.

5.3 Recommendation for further research

More research is needed to investigate the specific pests that emerge when climatic patterns change. The constraints that gender, with its land-use conflicts, impose on smallholder farmers ‘efforts to adapt to climate change should be research on. Nonetheless, the findings indicate that adopting CSPM practices and utilizing technologies, particularly in Sub-Saharan regions with heterogeneous agro-ecological zones and heavy reliance on subsistence agriculture, necessitates localised solutions in policy formation and planning of both agricultural extension services and development interventions that take farmers' agency into account.

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APPENDICES

Appendix 1: Questionnaire for farmers

Introductory and consent statement:

Dear Sir/Madam,

I am employed by the International Center for Insect Physiology and Ecology (ICIPE). A survey is being carried out to investigate the opportunities and barriers to adopting Climate-Smart Pest Management technologies (parasitoids, push-pull, biopesticides, traps, etc.) as well as the role of digital tools in the adoption of these technologies. Your household's responses to these questions will be kept confidential. Participation in this study is entirely voluntary; if you do not wish to participate, you are free to do so.

Do you consent to share information? 1=Yes, 0=No.

MODULE 1: HOUSEHOLD INDENTIFICATION, COMPOSITION AND VILLAGE IDENTIFICATION

Household Identification	Co de	Interview details
M1. Country UGANDA		**M13**. Date of interview (dd/mm/yyyy):
M2. District:		**M14**. Name of interviewer:
M3: Sub County:		
M4: Village**:**		
		GPS reading of homestead
M5. Name of the respondent:		**M15.** Latitude (North):
M6. Sex of the respondent 1=Male; 0=Female		**M16.** Longitude (East):
M7. Age of the respondent in years		**M17.** Altitude (meter above sea level)**:**
M8. Name of household head:		
M9. Sex of household head 1=Male;0=Female		
M10. Name of spouse (only for male headed households):		
M11. Number of members in the household		
M12. Education level of respondent (1= None, 2= Primary, 3= Secondary, 4= Tertiary certificate, 5= Diploma, 6= Undergraduate degree, 7= Masters, 8= PhD; 9= religious education)		

MODULE 2: LAND OWNERSHIP, LAND CROP PRODUCTION

M2.1 Do you have access to land farming? Yes=1; No=0

M2.2 farm size under tomato and production (Acres) (M 2.2) ………………………………

M2.3 Total size of land that in your possession (acres) (M2.3) ……………...

M2.4 Mode of acquisition (M3.3)
(**CODE2.4**:1=inherited;2=purchased;3=rentedin;4=borrowed;5=communal/givenbyvillagechief;6=sharecropped)

M2.5FNumber of years in tomato farming (M2.5) 1= less than one year; 2= one to five years; 3= six to ten years; 4=ten to twenty years.

M2.6 Except tomato, which other major crop do you grow on your land? (M2.6) ....1= Maize, 2= Beans, 3= Onions, 4 =Bananas, 5= Snow peas, 6= Other...), 0=none

M2.7 Who is the household decision-maker in crop production? 1=Husband; 2=Wife;3= both/joint decision making

Module 3: KNOWLEDGE AND PERCEPTIONS OF TUTA ABSOLUTA (TA) AND CLIMATE SMART PEST MANAGEMENT TECHNOLOGIES(CSPM)

M3.1 Who do you consult to questions related to the control and management of crop pests? (M3.1) (Code 1 Module 4)

M3.2 Have you heard of Climate Smart Pest management technologies or non-pesticide for pest control? .... Yes=1; No=0

M3.3 Who told you or how have you learned about CSPM? (M3.3).................................(Code 1 module 4)

M3.4 Have you ever received training specific to CSPM?......................... Yes=1, 0=No

M3.5 If YES to M3.4, by whom? .... (Code 1 module 4)

M3.6 Has your household ever used any CSPM? .... Yes=1; No=0

M3.7 If yes to 3.6 which ones, have you used? (Tick more answers if applicable)

1=parasitoids, 2=pushpull, 3= biopesticides, 4=traps, 5=Screenhouse, 6=crop rotation, 7=monitoring, 8=use of plant extracts,

M3.8 If yes to 3.7, did you use it during the last 12 months?.............................. Yes=1; No=0

M3.9 If yes to 3.8, Who decide of the CSPM technology to adopt or purchase?......................... 1= Mostly

husband, 2=More husband than wife, 3=More wife than husband, 4=Mostly wife, 5=Other family members

M3.10 Do you know other farmers using CSPM? .... Yes=1; No=0

M3.11 How would you rank your use of these practices for pest control? (Rank your answers from 1 lowest to 5 highest (M3.7) (code 3.7)... (Code 3.7: a: chemical pesticide; b: Bio-Pesticide; c: Crop rotation; d: hand pulling; e= Cow urine; f=Trap; g= Parasitoid; h= Push pull; i= screenhouse; j: destroying infected plants; k: organic pesticide; l=inorganic pesticide, l: Other method)

M3.13 Who is in charge of pest control?...................................1=Husband, 2=Wife,3=Both, 4=other family member

Perception of tomato pests and CSPM technologies	**1= strongly disagree, 2= disagree, 3= Do not know, 4= agree, 5= strongly agree**
Tuta absoluta (TA); major threat to tomato production on your farm	
TA reduce the quality of tomato produce	
TA result in high loss of tomato market value	
TA are induced by climate change	
TA/FAW are not harmful to human health	
You report pests' infestation to agricultural extension services	
Extension service providers give helpful advice on management and control of pests	
Chemical insecticides alone can effectively control tomato pest like TA	
Chemical insecticides endanger human health.	
Chemical pesticides are hazardous to the environment.	

There are other alternatives to chemicals pesticides for pest control	
Parasitoids are natural enemies	
CSPM (e.g.: parasitoids, push pull, greenhouse) are not harmful to human	
CSPM are affordable to farmers	
Farmers using CSPM improve crop yield	
CSPM reduce chemical output to the environment	
Our cultural belief does not allow parasitoid use	

MODULE 4: INSTITUTIONAL SERVICES

M4.1 Have you received extension service within the last 12 months (M4.1). Yes=1; No=0

M4.2 If yes to 4.1 have you received any extension service on tomato production? (M4.2) Yes=1; No=0

M4.2 If yes to 4.1 have you received any extension service on tomato production? (M4.2) Yes=1; No=0

M4.3 If yes to 4.2, on what aspects on tomato production did the extension focus? Code 3

M4.4 Source of the extension ..... code 1

M4.5 How was if done?. ....Code 2

M4.6 Are you a fellow of any Farmer's association?. Yes=1; No=0

M4.7 If yes to 4.6 How many?..............

M4.8 how many years since you join? (Years)…………...

M4.9 What is/are the roles of the associations?..

M.10 Approximated distance to the market from residence(kms)……………….

M4.11 Distance to the nearest agricultural extension office (Kms)………………...

Code 1	Code 2	Code 3
1. Ministry of Agriculture 2. Ministry of health 3. District committee 4. Village committee 5. Farmers organization 6. Local political leaders 7. Support organization 8. Private consultant 9. Neighbor/friend 10. Extension officer 11. Other	1. Government to farmer 2. Farmer to farmer 3. Private provider to farmer 4. other	1. offers advice and information 2. alert about *Tuta absoluta* 3. help fight *Tuta absoluta* 4. increase the efficiency of the family 5. increase productivity 6. mobilization of funds 7. information about parasitoids 8. information about push pull 9. information about biopesticides 10. information about pheromones traps 11. access to seeds 12. access to fertilizers 13. weeding and land preparation 14. spraying and pest management 15. credit access 16. harvesting and post-harvest handling/ marketing 17. other

MODULE 5: CLIMATE CHANGE VARIABILITY; AWARENESS AND EFFECTS ON TOMATO PRODUCTION.

M5.1 What variations in the rainfall have you observed since 20 to 35 years? (M5.1) **(Code5.1) ....**

(code5.1: 1= Increased; 2=Decreased; 3=No change;4=No idea**)**

M5.2 Have you observed any variance in temperature over the past20to35years? (M5.2) **(Code 5.2)**

(Code 5.2:1=Increased;2=Decreased;3=Nochange;4=No idea**)**

M5.3 Is there any change in the crops (tomato/maize) farming seasons for long rains? (M5.3) (code 5.3) Tick more answers... (Code 5.3: 1= Late rainy season; 2= Early rainy season;

3= shortening of rainy seasons, 4= interrupted rainfalls, 5=drought (missing rainy seasons), 6= No change; 7= no idea

M5.4 Is there any change in the crops(tomato/maize) farming seasons for short rains? (M5.4) (code 5.4) Tick more answers... (Code 5.4: 1= Late rainy season; 2= Early rainy season;

3= shortening of rainy seasons, 4= interrupted rainfalls, 5=drought (missing rainy seasons), 6= No change; 7= no idea

M5.5 How would you rate these climate related disasters? (M5.5) **(Code 5.5:** 1= High; 2= Medium; 3= low; 4= no idea)

Drought…**…………** Flood………………...Invasive pests……………………….

Other…………………………

M5.6 How would you rate the proliferation of Invasive pests over the past 10 to 20 years? (M5.6) (**code5.6**) ....(**Code 5.6**: 1=High; 2=medium; 3=low; 4= no idea)

M5.7 How often pests are monitored? (M5.7) (**code5.7**)

(**code5.7**:1=Daily;2=Weekly;3=Monthly;4=Onceduringgrowingseason;5=During specific pest outbreaks; 6= None)

M5.8 How pests are monitored? (M5.8) (**code5.8**) ....(**code5.8**:1=Visual inspection; 2=Pheromonetraps;3=Stickytraps;4=Coloredtraps;5=Lighttraps;6=none

M5.9 Who is monitoring pests?...............................1=Researcher,2= extension officer, 3=husband, 4=wife, 5=children, 6= agricultural organization, 7= other specify

MODULE 6: BARRIERS FOR UPSCALING CLIMATE SMART PEST MANAGEMENT TECHNOLOGIES

M6.2.1 Do you have limited access to farming land? (M6.2.1) Yes=1, No=0

M6.2.2 Do you have access to appropriate CSPM handling tools (certified seed, pheromones, parasitoids cages)? (M6.2.2) Yes=1, No=0

M6.2.3 Are you able to afford any CSPM technologies? (M6.2.3)....... Yes=1, No=0

M6.2.4 How do you perceive the cost of any particular CSPM such as screenhouse/push pull seeds? (M6.2.4)

…………1=high; 2=Medium; 3=Low; 4=Do not know

M6.2.5 Do you have enough facilities for storing, protecting CSPM from theft? (M6.2.5) Yes=1, No=0

M6.2.6 Is CSPM use not practical to be implemented in your farm? (M6.2.6) Yes=1; No=0

M6.2.7 Doyouhaveadequatephysicalandsocialinfrastructuressuchas roads, markets, storage facilities that allow ease adoption? (M6.2.7) Yes=1,No=0

M6.1.1 How familiar are you with CSPM? (M6.1.1) **(code6.1.1:1=**Familiar with concepts and practices;2=Never heard of them;3=Not sure what are they; 4= Regularly use CSPM)

M6.1.2 Yes=1, No=0 Have you been trained on the handling of any CSPM? (Yes=1, No=0)

M6.1.3 Do you think the national and local government promote the adoption of CSPM technologies? Yes=1; No=0

M6.1.4 Do your cultural believes not allow you to adopt CSPM such as parasitoids, pushpull? (M6.1.4) …. Yes=1, No=0

M6.1.5 Does gender issue play an important role in the adoption of CSPM? (M6.1.5) Yes=1, No=0

M6.1.6 Do you have the right, as a farmer, to participate in the decision-making process for CSPM adoption? (M6.1.6) Yes=1, No=0

Module 7 Opportunities associated with CSPM

M7.1 Effect of CSPM in Pest reduction (M7.1) **(Code:7.1**) ....(**code 7.1**: 1=high; 2= Medium; 3=Low; 4=None)

M7.2 Contribution of CSPM to the reduction of chemical pesticides use (M7.2) **(Code:7.2**) ....(**code 7.2**: 1=high; 2= Medium; 3=Low; 4=None)

M7.3 Do you think CSPM are easily manipulated? (M7.3) Yes=1, No=0

M7.4 What is the effect of CSPM in strengthening farmer's resilience (M7.4) **(Code:7.4**) ....(**code 7.4**: 1=high;

2= Medium; 3=Low; 4=None)

M7.5 Possible positive impact of CSPM use on crop quality (M7.5) ....1=high; 2=Medium; 3= Low; 4=None

M7.6 Contribute to lower risk of environmental pollution? (M7.6)Yes=1,No=0

MODULE 8: DEPENDENCY, USE, PRESERVATION AND RECORD KEEPING

M8.1to what level do you depend on these CSPM for pest control? (M8.1) (**code 8.1**: 1= Entirely; 2=

a=parasitoids, b=pushpull, c= biopesticides, d=traps, e=Screenhouse, f=crop rotation, g=monitoring, h=use of plant extracts,

M8.2 what do you do to minimize CSPM technologies destruction in your farm? (M8.2) …………….. (**code8.2**:1=minimizepesticideuse;2=usesystemicandselectivepesticide;3=growplantsrichofpollen and nectar; 4= none, 5=other specify………

M8.3 Do you keep records of pest species names? (M8.3) .... Yes=1; No=0

M8.4 Do you keep records of control practices used over time? (M8.4) ....Yes=1; No=0

M8.5 Do you keep records of pest monitoring data? (M8.5) ....Yes=1; No=0

M8.6 Do you keep records of parasitoids species released? (M8.6) Yes=1; No=0

Module 9: Role of digital tools (mobile Phones, Tv, Radio…) in the adoption of CSPM technologies

9.1 Types, Accessibility of tools and challenges

M9.1.1 Do you own a mobile phone? Yes=1; No=0

M9.1.2 Do you use your mobile phone for agronomic information (about pests' control, farming, weather)?. Yes or No

M9.1.3 If no, why? 1= no network, 2= power shortage,3= illiteracy, 4= unaffordability of smartphone, 5=inability

to trace and call back, 6=language barrier, 7= Security, theft, 8= bad weather condition 9=other specify

M9.1.4 Do you own a TV? Yes=1; No=0

M9.1.5 Do you use your TV for agronomic information (about pests' control, farming, weather…...)? Yes or No

M9.1.6 If no, why?.........1= no network, 2= power shortage,3= illiteracy, 4= unaffordability of Tv, 5= inability to manipulate the Tv, 6=language barrier, 7= Security, theft, 8= bad weather condition 9=other specify

M9.1.7 Do you own a radio? Yes=1; No=0

M9.1.8 If no, why? 1= no network, 2= power shortage,3= illiteracy, 4= unaffordability of Radio, 5= inability to

manipulate the Radio, 6=language barrier, 7= Security, theft, 8= bad weather condition 9=other specify

M9.1.9 Do you own other digital tools? If yes which?..............

M9.1.9 if no to 9.1.8 what could be the reason? = I am not aware of CD/DVDs contain this information, 2= I

cannot afford to buy, 3= I do not have a laptop to read., 4= Others specify ....

M9.1.8 In what form does the information reach you?.......... 1=Text message; 2= Voice message; 3= Video message; 4= Other (specify)

M9.1.9 In what language does the information come? .... 1= English; 2=French; 3= Other (specify)

M9.1.10 How often do you receive the information?................1= Every day; 2= Every two days; 3= Weekly; 4= Monthly; = Other (specify)………………………...

9.2 Use, Perception of digital tools

M9.2.1 Rate the use of each of these digital tools to acquire the information below: 1 being less used and 5 being highest use

	Crops Cultural practices	Pest outbreaks	Spraying of chemicals	CSPM practices/ technologies	Weather information	Access to seeds	Credit access	Harvest and post-harvest method	Market/selling prices
phone									
Tv broadcas t									
Radio									
Social media (Facebook/ WhatsApp)									
CD, DVDs, flash disks									
Other									
Impact of information									
Frequency									

NB: **Impact of information**: refers to how useful and reliable is the information. Rank from 1 being insignificant and 5 being very useful and very reliable

Frequency: it refers to how often do you receive this information: 1= Every day, 2= Weekly; 3= Monthly; 4= seasonally; 5= yearly

M9.2.2 Do you think digital tools can help in control practices? .... 1=strongly agree, 2=agree,

3=strongly disagree; 4=disagree; 5= don't know

M9.2.3 How long have you been receiving information from these digitals' tools?

1= one week; 2= one month; 3= one year; 5= since 5years; 6= in the last 10 years ago; 7= almost 20 years

Thank you!

Appendix 2: After a training with NARO team about CSPM project in Uganda

Source: Author, 2022

Appendix 3: Local leader sensitizing farmers about the environmental and socio-economic relevance of the survey in Mbale District

Source: Author, 2022

Appendix 4: Surveying with a tomato smallholder female farmer

Source: Author, 2022

Appendix 5: Crossing the river in the evening hours to conduct a survey

Source: Author, 2022

Appendix 6: Monitoring the *Dolichogenidea gelechiidivoris* parasitoid in a tomato farm

Source: Author, 2022