THE RESPONSES OF INSECT PESTS TO A CHANGING AND VARIABLE CLIMATE IN ZIMBABWE

By

Rumbidzai Debra Chapoto

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PIETERMARITZBURG

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DECLARATION

I, **Rumbidzai Debra Chapoto**, declare that:

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As research supervisor I agree to submission of this thesis for examination

Signed……………………………………………… Date……………………………..
(Professor Paramu L. Mafongoya: Main supervisor)

Signed …………………………………………….. Date……………………………..
(Dr Augustine Gubba: Co-supervisor)

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To my late parents (Joseph and Grace) and my family (Effort, Taropafadzwa, Tanyaradzwa).

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ABSTRACT

Climate change and variability cause direct yield losses as a result of adverse environmental conditions and indirectly through losses resulting from insect pests attack. The impacts of a changing and variable climate are more likely acute in the developing countries as a result of poverty and economic challenges which limit the farmers' capacity to adapt to risks associated with a changing and variable climate. Smallholder farmers in Zimbabwe are likely to face huge yield losses as a result of the changes in the abundance and distribution of insect pests.

The aim of this study was to evaluate the responses of insect pests to a changing and variable climate in Zimbabwe. The study was conducted in the five agro ecological regions of Zimbabwe also known as natural regions to determine the perceptions of the farmers to climate change and its impact on insect pests, farmer knowledge and practices to manage insect pests of vegetable crops in a changing climate, map emerging insect pest distribution in Zimbabwe using climatic data as well as to model future distribution of emerging insect vectors. A participatory research approach using the survey questionnaires, interviews and focus group discussions was employed in the study. The Random Forest (RF) modelling algorithm was used to map the current and the projected distribution of the emerging insect vectors.

Twenty two percent of the farmers across natural regions perceived changes in climate to be increases in temperatures throughout the year and an increase in the frequency of droughts. Late rainfall was cited by 16.4% of the farmers while long dry spells was cited by 16% of the respondents and 7.2% cited shorter cold season as the major indicator of a changing climate. Increasing incidence of heat waves, flash floods and the disappearance of wetlands and green spaces were cited as other indicators of a changing climate. Increased abundance of insect pests, decreased natural resource base and reduction in social safety nets were perceived to be the major climate change risks that were experienced by the smallholder farmers. The majority of the farmers (89%) have also expressed experiencing an increase in the incidence of insect pests such as aphids, stem borers, termites, diamond back moths, bollworms and whiteflies throughout the agro ecological regions of the country. Four percent perceived a decrease in insect pest incidence while 1% was not sure whether insect pests were increasing or decreasing. Farmers also perceived a change in behaviour of insects such as an increase in

mobility as cited by 50.8%, and colour variations within insect species as highlighted by 73.6% and emergence of new insect pests which was highlighted by 59%. The perceived crop production risks as a result of the changes in climate included an increase in the abundance of insect pests such as aphids, stem borers, termites, diamond back moths, bollworms and whiteflies.

The majority of the farmers (53%) cited high vegetable losses from insect pests and diseases. Farmer's insect management strategies that were implemented to manage the increasing insect pest population on vegetable crops included planting insect resistant vegetable cultivars, use of certified seed. All the respondents (100%) cited the use of chemical insecticides at some point during the production cycle of vegetables. A higher proportion (60%) perceived effective control of insects by chemical insecticides while 34% perceived reduced efficacy of the chemical insecticides and 6% were not very sure of effectiveness of chemical insecticides. Increased rates of application, increased frequency of chemical insecticide use and the use of hazardous insecticides has been cited by the majority of the smallholder farmers. There is need for facilitation of development and adoption of Integrated Insect Pest Management (IIPM) and raise awareness to avoid overdependence on chemical insecticides. Insect pest models that support adaptation planning also need to be developed to forecast climate change events, the distribution of insects in space and time and the corresponding pathogens that are transmitted by these insect pests.

A study was also conducted to map the current aphid, *Myzus persicae* and whitefly, *Bemisia tabaci* distribution in Zimbabwe using the summer and the winter data set from field surveys and the RF model. Precipitation and temperature related variables were found to be important in affecting the spatial distribution of aphids and whitefly. In addition the summer dataset was considered to be more reliable in mapping the distribution of both the aphids and the whiteflies. Using the RF model, the conducive environmental conditions for aphid and whitefly infestation are more pronounced in the northern part of Zimbabwe while the southern part of the country is less suitable for both the aphid and whitefly infestation. Based on the level of infestation, the results for aphid distribution produced an overall classification accuracy of 70% and a kappa value of 0.64. An overall accuracy of 75% and a kappa value of 0.67 was produced for whitefly distribution, whereby a kappa value represented the extent to which the data collected in the study are correct representations of the variables measured. In this study a kappa value 0.64 and 0.67 indicated that the data was reliable in determining the current distribution of the aphid and whitefly.

Higher rainfall areas which include Nyanga, Chipinge, Goromonzi, Rusape and Murewa, are currently more suitable for aphid infestation than the low rainfall areas such as Masvingo, Chiredzi and Hwange. Spatial and temporal projection of the suitability of various agro ecological regions to insect vectors of significance in Zimbabwe is critical in enabling timely planning of management and preventative measures in the areas where the insect vectors are expected to occur under future climate conditions.

For whitefly distribution in 2050, the overall accuracy was 70% with a kappa value of 0.62. For the year 2080, the overall accuracy was 65% with a kappa value of 0.55. The susceptibility of Zimbabwe to whitefly was persistent throughout the years modelled. Whiteflies have potential habitats in the northern areas of Zimbabwe while the central part will be less conducive to the development of whitefly infestations by 2050. By the year 2080 the levels of whitefly infestations will decrease in the lowveld, the central and the western parts of Zimbabwe. However, the habitat suitability range will increase in areas south of Gutu, west of Chipinge and south west of Magandani. The findings of this study highlight the potential for using the vulnerability maps to inform whitefly surveillance at spatial and temporal ranges.

Overall, the study showed that increasing temperature and altered precipitation patterns in Zimbabwe have the potential to increase the distribution and the abundance of insect pests. This is likely to increase the use of chemical insecticides thereby exposing the farmers and the consumers to the hazards associated with overuse of chemical insecticides. The sub humid and the sub-tropical regions of the country are currently and potentially suitable habitats of a wide range of insect pests including the virus vectors. The more arid regions are currently less suitable and will become unsuitable for the virus vectors in future. Government intervention through insect surveillance at both spatial and temporal scales is of importance in reducing yield loss as a result of insect pest hazards. Early warning systems to increase farmer awareness on the impending insect pests' hazard and policies to reduce overuse of insecticides is of importance under changing climate conditions. Promoting the use of alternative insect pest control strategies in these regions which are likely to be suitable for insect pests is also vital for a more efficient management of insect pests thereby reducing crop losses to due to insect pest attack.

CHAPTER 1

INTRODUCTION TO THESIS

1.1 Rationale of the study

The changing and variable climate is projected to alter the environmental conditions beyond the usual farmers' experiences in many regions of the world (Gornall et al., 2010). These conditions are most likely to continue despite the various efforts that are being put in place to mitigate the emission of greenhouse gases into the atmosphere (IPCC, 2013; Ramirez-Villegas et al., 2013). This implies that climate induced risk management and adaptation is of importance in reducing vulnerability and food insecurity particularly among the smallholder farmers who are characterised by a low adaptive capacity (Stringer et al., 2012; Rufino et al., 2013). Although climate change and variability is a global phenomenon, its impacts are diverse in various localities. Both positive and negative results depending on latitude, altitude, type of the crop and the economic situation of the nations are obtained as a result of a changing climate (IPCC, 2013). There are, however, more negative than positive impacts in developing countries such as Zimbabwe because of its geographical location, higher levels of poverty among the smallholder farmers and over reliance on rain fed agriculture (Gurukume, 2013).

Climate change and variability affects crop yields through direct yield losses attributable to adverse environmental conditions (Mapfumo et al., 2013) as well as through the changes in population dynamics and geographic distribution of crop pests (Khan et al., 2014). Many assessments of climate change effects on crops have focused on the potential yields, but factors such as insect pests and pathogens which have major effects in determining actual crop yields have not been taken into consideration (Gregory et al., 2009). Climate change is likely to increase the spread of plant pathogens by insect vectors in a number of crops. Due to the ectothermic nature of insects, they are very likely to respond quickly to warming temperatures (Robinet & Roques, 2010). The warming temperatures therefore have the potential to affect most life history parameters of insect pests (Chidawanyika et al., 2012).

In the African continent various researches have been conducted linking climate change with farmer vulnerability (Mano & Nhemachena, 2007). In Zimbabwe, research has been carried out to determine the vulnerability of the agricultural system to weather variables (Mapfumo et al., 2013). However, very few studies have focused on the vulnerability of smallholder farmers to yield losses as influenced by insect pests and diseases in an environment of a changing and variable climate. There is, thus, a gap in assessing smallholder farmer's knowledge and perceptions to insect pests and diseases as influenced by a changing and variable climate (Adam et al., 2015). In addition, the majority of the studies on insect pest distribution under a changing climate have mainly been conducted in developed countries (Barredo et al., 2015). The use of insect pest models in predicting and quantifying the present occurrence and projected distributions of established insect species in distribution studies is an important step in establishing surveillance monitoring when the potential distribution of the insect pest is established (Gormley, 2011). The projected distribution of insect pest will, therefore, increase better preparedness to reduce outbreaks of serious insect pests as a result of climate change and variability (Fand et al., 2014).

Despite the significant contribution of smallholder agriculture to agricultural output and to global food production (Hazell et al., 2007), these farmers are susceptible to the adverse environmental conditions as well as the associated risks (Gurukume, 2013). From the year 1980-2010, fifteen dry seasons coupled with temperature extremes in the moderate to extreme drought range have been recorded in Zimbabwe, whilst the hottest period was 2000-2010 with 8 droughts resulting in direct yield loss (Meteorological Services Department, 2013). These weather conditions are likely to cause changes in population dynamics of insect pests in Zimbabwe.

Zimbabwe is divided into five distinct agro ecological regions based on rainfall quality, temperature regimes and soil quality (Anderson et al., 1993; Vincent and Thomas, 1960). This implies that the various regions have various susceptibilities to insect pests as a result of the variations in the agro ecosystems. A variety of insect pests have emerged and caused devastating losses to the production of both horticulture and field crops in the various agro ecological regions in the recent agricultural seasons in Zimbabwe. The incidence of insect pests which destroy crops such as sugarcane like black maize beetle, *Heteroncychus licas*, Klug (Coleoptera: Scarabeidae) and pearly scale, *Margarodes spp*, Morales 1991 (Hemiptera: Margarodidae) will be severely affected by temperature increases. Besides other biophysical factors, the emergence of black maize beetle is stimulated by high temperatures which are associated with a warming climate (Chandiposha, 2013). In addition to the black maize beetle and the pearly scale in sugarcane production in Zimbabwe, the termite (Isoptera: Termitidae) and nematode, *Pratylenchus zeae*, Graham 1951 (Tylenchida: Pratylenchidae) populations is expected to increase due to warm and dry conditions that are associated with climate change (Clowes & Breakwell, 1998).

In the production of the golden leaf, tobacco in Zimbabwe, there has been an occurrence and subsequent domination of the red morph of tobacco aphid, *Myzus persiace nicotianae*, Sulzer (Hemiptera: Aphididae) compared to the green morph of the aphid. The red morph was reported to be tolerant to higher temperatures as well as resistant to a variety of insecticides (Masukwedza et al., 2013). In the Southern lowveld of Zimbabwe, spotted stem borer, *Chilo partellus* Swinhoe (Lepidoptera: Noctuidae) exhibits a facultative diapause and causes extensive damage to both rain fed and off-season irrigated cereal crops (Chinwada et al., 2001).

In Zimbabwe, invasive insect species have been reported during the 2016 agricultural season mainly in agro ecological regions 2 and 3 which are characterised by intensive agricultural production. There has been a sudden outbreak of tomato leaf miner, *Tuta absoluta* Meyrick (Lepidoptera: Gelechidae) a new invasive and highly destructive pest, to the majority of crops in the solanaceous family towards the end of the year 2016. Its ravaging effect on the tomato plants resulted in the loss of up to 80% of the tomato yield. Other affected crops include tobacco, potato, pepper, eggplant and even weeds that belong to the solanaceous family. In severe cases, the leaf miner has been reported on vegetables that belong to the brassica family such as cabbage and kale. In tomatoes the pest caused heavy economic losses resulting in increase in the prices of tomatoes.

In addition to the tomato leaf miner, in the 2016/2017 agricultural season, there has been a sudden emergence of an armyworm in Zimbabwe, fall armyworm, JE Smith *Spodoptera frugiperda* (Lepidoptera: Noctuidae). The fall armyworm is widely distributed in eastern and central North America and in South America (Murua et al., 2009) and suddenly, it invaded Zimbabwe. This implies that the country is and will be at risk from numerous insect pests that are not common in Zimbabwe and also there is likely to be sudden outbreaks of insect pests that affect agricultural crops in Zimbabwe.

1.2 Conceptual framework

This research study was guided by the conceptual framework shown on Fig1.1. It shows that the underlying factors that determine farmer's adaptation to a changing and variable climate are the knowledge and the perceptions of risks posed by climate change and variability. The framework highlights the need for smallholder farmer adaptation to the insect pest problem which is of critical importance in ensuring sustainable crop production in the face of climate change and variability. Farmer knowledge and perceptions are of importance if they are augmented with climate change projections as well as the projected insect pest distribution models.

Climate change adaptation is defined as the adjustments in processes and practices, to reduce the potential damages or to benefit from opportunities associated with climatic stimuli as well as their impacts (Smit & Pilifosova, 2001). In agriculture, the climatic variables with the greatest impact are variability and extremes rather than the average conditions (IPCC, 2013). Smit & Wandel (2006) defined adaptation as the adjustments made by humans which they can utilise in order for them to better manage or adjust to changing conditions, stress, hazards, risk or opportunities. They also included cultural adaptation, which refers to the process in which groups of people develop or adopt new and improved methods and technologies to their cultural values in order to cope with the environment (Smit & Wandel, 2006; Tompkins & Eakin, 2012).

An understanding of the perceptions and adaptation strategies of individual households or communities in an area provide better insights into management practices. This helps to generate additional information which are relevant to policy interventions to address the challenge of sustainable crop production and development in the context of a changing and variable climate. Adaptation is a feature that has made it possible for the survival of biotic species alongside the harsh climatic conditions (Depledge & Lamb, 2005). However, climate change and variability brings with it new challenges that require new interventions to support adaptation. It is because of those impacts and vulnerabilities that need for adaptation is strongly justified (Paavola & Adger, 2006).

Climate change and variability generally affects temperature, rainfall and wind speed and wind duration in areas or regions that are exposed to the harsh environmental conditions. These weather variables are the most important factors influencing insect pest population dynamics (Parvatha, 2015). The increases in insect pests' problems can be reduced by the adoption of a variety of strategies. Development of gene pools for crop varieties that resist insect pest attack can also be developed in the future. Monitoring of existing insect pests and development of insect pest models will be of importance in reducing smallholder farmers vulnerability to yield loss as a result of insect pest attack, thereby ensuring sustained crop production and hence food security.

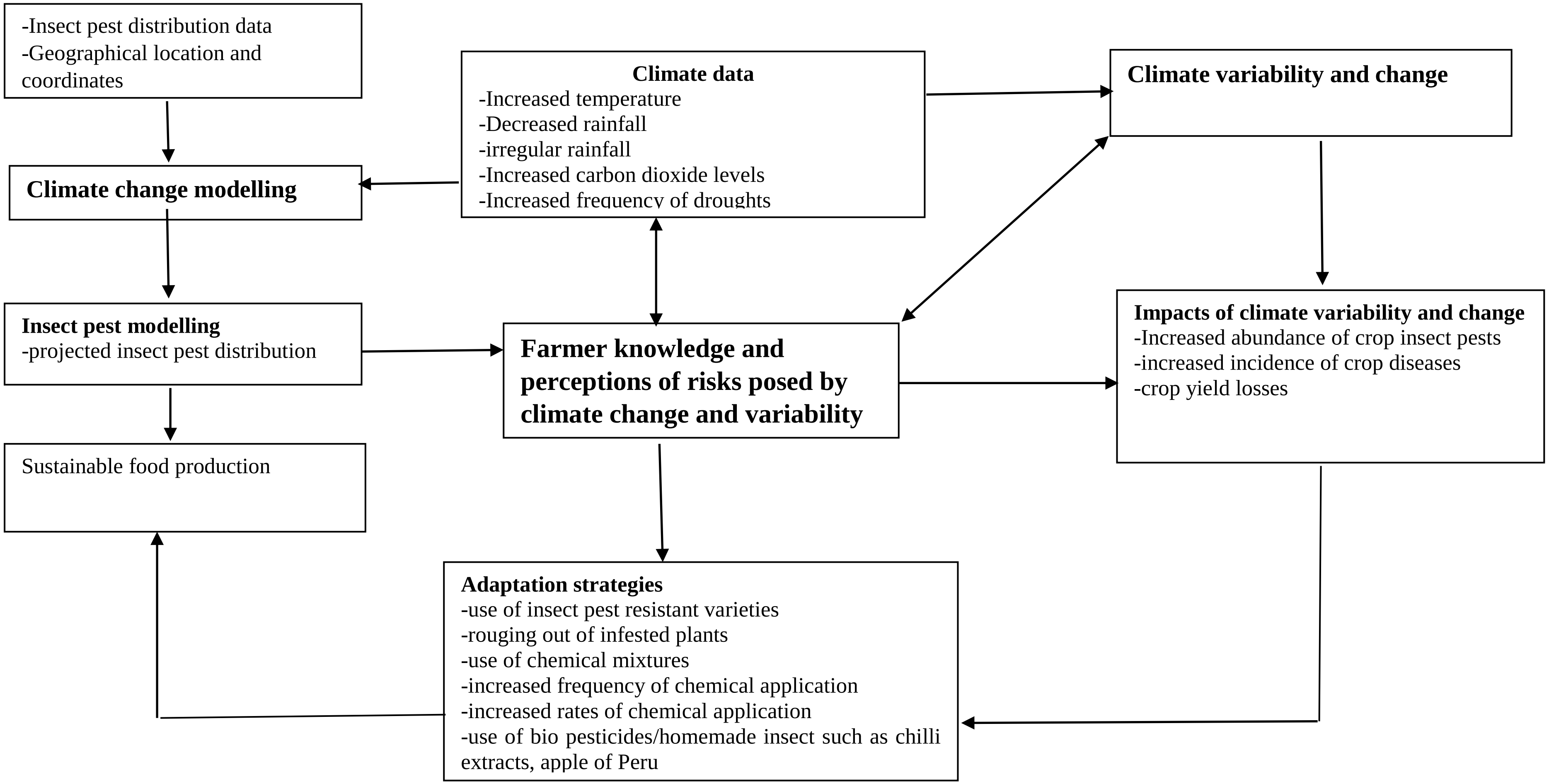

Fig 1.1: The conceptual framework for the study
(Author's own construction)

1.3 Justification of the study

Zimbabwe lies in the tropical to sub-tropical regions with a high degree of variable rainfall patterns as well as temperature fluctuations (Brown et al., 2012). Zimbabwe's daily minimum temperatures have risen by approximately 2.6˚C while daily maximum temperatures have risen by 2˚C during the 20th century (Brown et al., 2012). The period stretching from 1980 to the first decade of the 21st century has been the warmest since first temperature records were done in Zimbabwe. Future scenarios predict further increases of between 1.3˚C and 4.6˚C by the year 2100, representing warming rates of between 0.1˚C and 0.4˚C per decade (Government of Zimbabwe, 2013). Being landlocked, Zimbabwe is most likely to warm more rapidly in the future than the global average. By the year 2080, annual rainfall averages are projected to range between 5% and 18% less than the 1961-90 average (Unganai, 1996).

Considering the climate change projections, there is need for evaluation of farmer perceptions to a changing and variable climate and the corresponding insect pests which are a major threat to crop production in a warming climate. The adaptation measures which farmers take to reduce the impact of increased pest problems and the development of predictive models will complement and augment current adaptation strategies in the face of changes in insect pest dynamics under a warming climate.

Climate change and variability will exacerbate the already available serious challenges to crop production and food security in most dry lands of the developing world (Knox et al., 2011). The elevated temperatures which is one of the major characteristics of a changing climate may lead to proliferation of insect pests and plant diseases (Luedeling et al., 2011) resulting in 30-50% of the yield losses in agricultural crops (Kroschel et al., 2010). Insect pests cause crop damage and loss in various ways and are mostly associated with the direct impact of their feeding resulting in yield loss, a reduction in the quality of harvested produce due to cosmetic damage as well as through the transmission of plant viruses (Fagelfors, 2009). More than half of Zimbabwe's land area is made up of arid and semi-arid lands therefore adaptation to the crop production risks caused by climate change and variability is a priority since the majority of the population in these areas are dependent on agriculture for their livelihoods (Gurukume, 2013). Farmer adaptation is of importance in reducing vulnerability to yield losses resulting from climate change hazards (Sarr et al., 2015).

Adaptation strategies are also of importance because the weather patterns have already changed and the changes are expected to continue even if mitigation measures are instantly put into place (Cobon et al., 2009).

Although there are many factors involved in climate change, the study will help to predict the impact of climate change on insect pest and resultant plant diseases that are transmitted by the insects. This will thereby assist the nation in the development of more efficient food security policies (Chidawanyika et al., 2012; Kihupi et al., 2015; Ramirez-Villegas & Thornton, 2015). A more accurate forecasting of pest incidence before they actually take place is desired in pest control programmes, so that control measures can be planned well in advance and also with maximum efficiency to increase food security (Prabhakar, 2012; Okonya et al., 2013). Plant pathogens such as viruses cannot be cured once a plant is infected by the viruses, the majority of which are transmitted by the insect vectors. Disease management and prevention of yield losses as a result of plant viruses must therefore aim to prevent the infection of plants and minimise economic losses through monitoring and taking necessary measures to get rid of the insect vectors (Vuorinen et al., 2004).

1.4 Hypotheses

1. Smallholder farmers in the five agro ecological regions perceive climate change as a major factor underlying increased insect pest abundance
2. Adaptation options for insect pest management in a changing climate are based on farmer knowledge of climate variability and change and the indigenous knowledge practices
3. Insect pests will become more abundant in higher rainfall and relatively lower temperature areas of Zimbabwe under future climate conditions

1.5 Objectives

The main objective of this study was to determine the responses of insect pests to a changing and variable climate in Zimbabwe based on farmers' perceptions and the various adaptation strategies to reduce vulnerability to insect pests' problems and hence yield losses. This study mapped the current distribution of an emerging insect vector (aphid) under climate change in Zimbabwe to determine the level of farmer vulnerability to this insect pest in the various agro ecological regions of the country. This research also projected the potential distribution of the key virus vector, whitefly (*B. tabaci*) under future climates.

The specific objectives of the study were:

1. To determine farmer perceptions on insect pests responses in relation to climate change in Zimbabwe.
2. To assess farmer knowledge and adaptation practices that are implemented to manage insect pest population on vegetable crops in a changing climate.
3. To map the emerging insect pest, *M. persicae* distribution in Zimbabwe.
4. To project the potential distribution of the whitefly, *B. tabaci* in vegetable production in Zimbabwe under future climate conditions (2050 and 2080).

1.6 General methodology and study approach

A participatory research method was used in the five agro ecological regions alternatively known as Natural Regions (NR). In this study, the 5NRs were represented by 5 districts of the Zimbabwe. The study used questionnaires using both structured and semi-structured questions, key informant interviews and focus group discussions. Data was subjected to Analysis of variance (ANOVA) using the Statistical Package for Social Sciences (SPSS version 16) to compare the responses of farmers across the natural regions. A Random Forest (RF) modelling approach was used to obtain information on the current and the potential distribution of the emerging insect pests which are of significance in the transmission of major plant viruses.

1.7 Organization of the Thesis

The different chapters of this thesis were compiled in a research paper format where each chapter was an independent research paper. The first chapter briefly describes the purpose and significance of this research. It outlines the research gap in climate change studies which has necessitated this research. The second chapter explores current knowledge, findings, as well as theoretical and methodological contributions of researches on the influence of abiotic factors on the biology (growth, reproduction, dispersal) of insect pests, the role of abiotic factors on the incidence of entomopathogens and plant-insect interactions under a changing climate. Chapter three determines the perceptions of farmers to climate change and variability and the corresponding insect pests of agricultural crops across Zimbabwe's agro ecological regions. Chapter four investigated farmer knowledge to a changing and variable climate in relation to key pests of vegetable crops and the adaptation strategies to cope with increasing insect pest populations under a climate change. The majority of the strategies were based on cultural means of managing insect pests as well as the use of chemical insecticides. In chapter 5, the present potential distribution of *M. persica* was mapped in Zimbabwe using the Random Forest modelling approach. The current and the projected distribution of whiteflies in Zimbabwe was mapped in chapter six. The whitefly distribution was projected for the year 2050 and the year 2080. Chapter seven consolidates the findings of the entire research, outlines the implications and highlights the issues of interests which can guide future research.

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CHAPTER 2

THE RESPONSES OF INSECT PESTS TO A CHANGING AND VARIABLE CLIMATE: A REVIEW

Abstract

Global climate change resulting from natural and anthropogenic factors has resulted in altered environmental conditions that are conducive for changes in abundance and diversity of insect pests. Insect pests, by being ectothermic in nature are most likely to respond to the changes in climate variables. The majority of climate change projections focus on crop yields and adaptation strategies to declining yields and ignore the likely impact of a changing climate on insect pests and plant diseases, yet the problem of insects and plant diseases is likely to be influenced by a changing climate. In this research paper, we present a review on the effects of climate variables namely temperature, carbon dioxide (CO_2), precipitation and extreme weather events on insect pests and plant diseases. Elevated temperatures, CO_2 and extreme weather events have been shown to increase the distribution, reproductive potential, the incidence and abundance of plant insects and diseases in temperate regions because of the dependence of insects and diseases on environmental conditions. There is limited information on the influence of temperature and carbon dioxide as well as their interaction on the incidence and severity of insect pests, bacteria and viruses in the tropical regions. Information on the influence of altered precipitation patterns is also limited but could be of importance in insect distribution studies in a changing climate. Tropical insects pests are likely to suffer from extreme heat resulting in death and hence pest extinction. Incidence and efficiency of entomopathogens are likely to be negatively affected by changes in the climatic conditions. Future research should focus on the interaction of elevated temperature and CO_2, determine the influence of supra optimal summer temperatures, temperature variability, precipitation variability and the responses of the various entomopathogens under tropical conditions. Modelling insect pest, climate change envelopes along with climate change in tropical areas such as the Southern African region will be of importance in determining insect pest distributions.

Keywords: elevated temperature, pests, changing climate

2.1 Introduction

Human activities and natural factors have led to rapid and extreme increases in atmospheric gases such as carbon dioxide and other greenhouse gases (IPCC, 2013). The increases in greenhouse gases have resulted in a number of observable climatic changes such as elevated temperatures (Jamieson et al., 2012), increased occurrence and severity of extreme weather events such as droughts, floods (Mearns et al., 2013) and intense tropical cyclones (Nissen et al., 2014). According to the Intergovernmental Panel on Climate Change (IPCC, 2007), the world's average temperature has increased by 0.07˚C for every decade in the 20^{th} century with the first decade of the 21^{st} century being the warmest period on record (AMCEN, 2011). There is also evidence that the rate of climate warming is increasing (IPCC, 2013) and the global climate change models predict a continued increase in atmospheric temperatures beyond the 21^{st} century, despite a reduction in the amount of gaseous emissions (Burrows et al., 2014; IPCC, 2013). On the other hand, CO_2 levels have increased from 280 ppm in 1750 to 368 ppm in the year 2000 (Watson, 2001). The levels are expected to increase to 1000 ppm by the end of the 21st century (Sanderson et al., 2011).

The increase in frequency and intensity of extreme weather events, changes in moisture conditions, temperature rises and elevated carbon dioxide concentrations are expected to magnify pest pressure on agricultural systems through range expansion of the existing pests and invasion by new pests (Parvatha, 2015). Accelerated pest development leads to increased number of pest cycles per season, disruption of temporal and geographical synchronization of insect pests, diseases, beneficial and predatory insects which will increase the risks of pest outbreaks (Jaworski & Hilszczanski, 2013). The extreme weather events is associated with the emergence of minor pests to major pests due to a reduction in host tolerance and changes in land use practices and landscape characteristics (Johnson et al., 2013) .

Due to the complex and highly variable responses of pests and their hosts to multiple and interactive shifts in environmental conditions, it is difficult to accurately quantify the potential impacts of climate change on pest damage. The changes in environmental conditions include elevated CO_2, changes in temperature and relative humidity, cloudiness, and shifts in rainfall patterns, wind patterns, land cover and land use changes. Extreme weather events (dry and wet conditions) are key factors in triggering endemic and emerging insect pest outbreaks (Anderson et al., 2004). The increased frequency of extreme weather events which is expected to occur as a result of climate change and variability is set to increase the agricultural pest burden. Dry periods tend to increase insect and viral outbreaks, while wet period encourage fungal and bacterial diseases and indirectly affect population dynamics of insect pests. Areas of concern for managing pests under climate change include pest range expansions, increased weed competitiveness, effects of root system pests on crop moisture stress and reduced effectiveness of integrated pest management (War et al., 2016).

In a changing climate, insect pests and plant diseases present a major threat to global crop production and food security (Chakraborty & Newton, 2011). However, many assessments of the effect of climate change on agriculture have focused on adaptation measures (Parvatha, 2015) and the potential impacts of climate change on crop yields (Moyo et al., 2012). Other yield limiting factors such as insect pests and crop diseases have been neglected in most of these assessments (Selvaraj & Pandiara, 2013). Therefore, there is a risk that future crop yields might be overestimated if the impacts of insect pests and plant disease epidemics are not taken into consideration (West et al., 2015). In the tropical areas, there have been few studies on the effect of global warming on insect pests of agricultural crops (Perkins et al., 2011) with the exception of hematophagous insects such as mosquito, *Anopheles spp* Say (Diptera: Culicidae) (Patz & Olson, 2006) and tsetseflies, *Glossina pallidipes*, Austen 1903, (Diptera: Glossinidae) (Terblanche et al., 2008). In addition temperate insect pests such as the coffee berry borer, *Hypothenemus hampei* Ferrari, (Coleoptera: Scolytidae) (Jaramillo et al., 2009) and the potato tuber moth, *Phthorimaea operculella* Zeller (Kroschel et al., 2013) have been researched upon yet tropical insects are at a greater risk from climate change as they inhabit the already warm environments (Zeh et al., 2012). The focus of this review is to collate information on the likely effects of climate variables such as elevated temperature, CO_2 and extreme weather events on insect pests and diseases in a changing climate. Detailed examination of the impact of respective climatic variables is discussed in this chapter.

2.2 The impact of elevated temperature on the biology of insect pests

Elevated temperature is one of the most important drivers of climate change that directly affect the timing of seasonal biological events of the majority of the arthropods, particularly insects (Altermatti, 2012; Miller-Rushing et al., 2010; Savopoulou-Soultani, 2012; William et al., 2015). The majority of insect pests are cold-blooded invertebrates and, therefore, do not use their metabolism to maintain their body temperature (Petzolet & Seaman, 2010), but depend on surrounding temperatures for all their biological activities such as development, distribution, reproduction and survival (Jaworski & Hilszczanski, 2013). Increases in the ambient temperatures may result in various changes such as a shift in geographical distribution, increased overwintering, changes in population growth rates, increase in the number of insect generations, extension of the insect development season and increased risk of invasion by migrant pests (Ahanger et al., 2013).

Elevated temperatures result in accelerated rates of development and increase in number of insect pest generations (Fand et al., 2012). This is achieved through a reduction in the length of the life cycle of insects (Newton et al., 2011; Seiter & Kingslover, 2013). Effect of elevated temperature on the length of larval development has been observed under laboratory conditions for two species of native foliophages, the nun moth, *Lymantria monacha*, Linnaeus 1758 (Lepidoptera: Lymantriidae) and the gypsy moth, *Lymantria dispar* Linnaeus 1758 (Lepidoptera: Erebidae) (Karolewski et al., 2007). For both insect species, increase in temperature had an influence on reducing the length of the life cycle, from egg phase to the pupal phase (Jaworski & Hilszezenski, 2013). It has been estimated that with a 2˚C temperature increase, insects might experience one to five additional life cycles per season and also produce more eggs (Yamamura & Kiritani, 1998). In a study that evaluated the biology of leaf hopper, *Nilavarpatha lugens*, Stal (Hemiptera: Cicadellidae) under elevated temperature in Asia, the short winged females deposited 48.1% more eggs in elevated temperature treatments than in ambient temperature treatments (Shi et al., 2014). In the same study, adults that were exposed to elevated temperature treatments emerged on average 1.3 days earlier than those that were exposed to ambient temperatures (Shi et al., 2014). In East Africa, in a study with the coffee berry borer using the CLIMEX model, a 2˚C increase in temperature was predicted to increase the number of generations as well as the damage by the coffee berry borer (Jaramillo et al., 2011). As a result of increased warming under changing climate conditions, earlier emergence and development of these insects is therefore anticipated (Jamieson et al., 2012) with the possibility of causing intense insect pest problems in the future. This suggests that insects will be able to produce more eggs in a given time period, complete their life cycles faster, which in turn may lead to population increases (Flower et al., 2014; Jamieson et al., 2012).

Warmer winter temperatures increase survival of insect pests during the season (Fand et al., 2012). The warm winter temperatures generally promote insect development at times of year when insect development would normally be suspended (Sharma et al., 2010; Sharma et al., 2013), leading to earlier insect activity in spring and late appearance of insects in autumn, for the majority of insect species (Fand et al., 2012; Jeong et al., 2011). A 1-5°C increase in mean temperatures in a climate change scenario would increase insect survival due to low winter mortality and increased population growth (Sharma et al., 2010), thereby increasing the rates of crop damage. In frost sensitive areas, increased warming results in a reduction in mortality events caused by chilling or freezing injury (Khaliq, 2014).This means that there will be an increase in insect survival and pest establishment in the areas that were previously unsuitable for the build-up of insect pest population as a result of extremely low temperatures.

Warmer environmental conditions will also allow insect pests to disperse to new regions from which they were previously excluded because of low winter temperatures (Parvatha, 2015). The insects shift their geographical location to higher-latitudes or higher elevation areas (Sharma et al., 2013). The migration of insects such as the cotton bollworm, *Helicoverpa armigera* Hubner (Lepidoptera: Noctuidae) a major pest of cotton, pulses and vegetables in North India is predicted to increase with increased warming from the southern parts of India (Sharma et al., 2010). This movement cause insects to adapt to new host plants thereby altering the structure, diversity and functioning of ecosystems (IPCC, 2007) and increasing the host range of insect pests (Jaworski & Hilszezenski, 2013). In a study that was conducted in Zimbabwe on coffee white stem borer, *Monochamus leuconotus* Pascoe (Coleoptera: Cerambycidae) it was predicted that the area suitable for the insect will increase in Chimanimani district by up to 200% by the year 2080 (Kutywayo et al., 2013). This suggests that some geographical areas that are too cold for certain insect species under the current climate scenario may become conducive under future climates. However, a contraction on population of vertebrate pests (Bellard et al., 2002) can also occur on insect pests that require colder conditions such as the armyworm, *Spodoptera spp* Hubner (Lepidoptera: Noctuidae) and tsetseflies (Mitrovski et al., 2008; Terblanche et al., 2008). This implies that in the temperate areas, the population of heat intolerant pests will shrink when temperatures in these regions increase from the present level.

Accelerated rate of metabolism of insects at elevated temperatures leads to increased size of insect and hence higher rates of crop consumption (Fand et al., 2012). The increased body size will be translated into improved insect fitness (Culliney, 2013). Increased insect fitness helps the insect pests to avoid natural enemies (Bell et al., 2015) therefore increasing insect pest population growth, reducing mortality under unfavourable environmental conditions and hence the likelihood of insect pest outbreaks.

The frequency and intensity of insect-pest outbreaks increase under elevated temperature conditions (Fand et al., 2012; Jaworski & Hilszczanski, 2013). Outbreak of Papaya mealy bug, *Paracoccus marginatus,* Heymans 1915 (Hemiptera: Pseudococcidae) resulting from elevated temperatures in Indian states (Karnataka and Maharashtra) resulted in significant yield loss to the papaya growers (Tanwar et al., 2010). Indirectly, high temperature conditions, increases crop susceptibility to attack by insect-pests because of the weakened plant defence system under climate warming therefore resulting in pest outbreaks and severe crop damages (Sharma et al., 2010). With the current global temperature rise and increased water stress, tropical countries like India may face the problem of severe yield loss in sorghum due to breakdown of resistance against midge, *Stenodiplosis sorghicola,* Coquilett 1899 (Diptera: Cecidomyiidae) and spotted stem borer, *Chilo partellus,* Swinhoe (Lepidoptera: Pyralidae) which lead to the outbreak of the insect pest in India (Sharma et al., 2010).

Extreme temperatures on the other hand can lead to heat induced coma and insect death in the tropical countries (Ma & Ma, 2012a). In an experiment where temperature was simulated in the study of brown plant hopper, *Nilaparvatha lugens* Stal (Hemiptera: Delphacidae) (a tropical rice pest) in India, the results of the effect of temperature on the insect indicated that the first instar nymphs became immobilized by heat stress at around 30˚C and among the more heat tolerant adult stage, no insects were capable of a coordinated movement when the temperature was increased to 38˚C. The insect did not recover after entry into heat coma, at temperatures around 38˚C for the nymphal stages and 42–43˚C for the adult stages (Piyaphongkul et al., 2012). The results of this study suggest that the brown plant hopper can become extinct in the future in the tropical regions when temperatures continue to rise as projected.

Insects can change their behaviour as a result of a change in temperature conditions (Ma & Ma, 2012a). Movement of insect pests from one part of the plant to the other is also a response to warmer leaf temperatures (Ma & Ma, 2012b). In a study in India, heat stress forced movement of insect pests rose-grass aphid, *Metopolophium dirhodum* Walker (Hemiptera; Aphididae) and cotton aphid, *Aphis gossypii* Linnaeus 1758 (Hemiptera: Aphididae) from the tender upper leaves to the bottom older leaves (Liu et al., 2000) where the cooler microhabitats in the lower leaves prevent heated injury to the aphids (Ma & Ma, 2012b). This implies that there is a possibility of insect pests to be constantly moving down the lower plant profile in response to high temperatures as a way of escaping heat stress in the upper storey of the plant.

Crop diseases are strongly influenced by climatic conditions (Legrève & Duveiller, 2010). The incidence of plant viral disease is also expected to increase with increasing atmospheric temperatures (Robinet et al., 2011; Malmstrom et al., 2011). The rates of vector transmitted diseases are increased by increased insect vector expansion, increased feeding activity, increased transmission rates and the potential for new insect vectors that are caused by elevated temperatures and the extended growing seasons (West et al., 2015). An increase in the incidence of viral diseases is predicted to occur due to either increased winter survival of insect vectors with increasing temperatures or early spring migration of the insect vectors (Mirski et al., 2012). In some experiments, warmer winters have been associated with an increase in viruses of many crops while warmer soils affect soil-borne viruses as the insect vectors will be able to infect crops at an earlier stage of crop growth (West et al., 2015).

2.3 Effect of elevated carbon dioxide on insect pests

Rising CO_2 levels in a changing climate may affect the distribution, abundance and performance of insect pests and plant diseases (Chakraborty et al., 2008). There is an increase in crop consumption by insect pests by at least 10% under elevated CO_2 levels (Gonzales-Vigil et al., 2011). However, the responses of insect pests to feeding activity at elevated levels of CO_2 levels vary with the type of insect species as well as its feeding habit (Hilstrom et al., 2010). Chewing insects such as the *Lepidopterans*, which chew and digest the whole leaf increase the rates of feeding upon the crops as a result of reduced nitrogen to carbon content and high amounts of defensive compounds under elevated carbon dioxide levels (Hughes & Bazzaz, 2001) resulting in compensatory feeding. Phloem and xylem feeding insects may be less affected by elevated CO_2 levels because they feed on plant sap, which is low in defensive compounds (Furstenberg-Hagg et al., 2013). Insect pests that feed on seeds also may be less affected by increased CO_2 levels because they maintain high levels of nitrogen in their reproductive system and hence have no need to acquire more nitrogen from the crops (Karowe & Migliaccio, 2011).

From the review, there is limited information on the direct effects of CO_2 on insect pests and diseases. There is need for more researches on the effect of CO_2 on insect vectors of tropical areas. More fungal pathogens were investigated under elevated CO_2 levels compared to plant viruses and bacteria. There is also need for factorial experiments to determine the combined influence of carbon dioxide and temperature in a tropical setting such as the Southern African region so as to come up with a more realistic assessment of the influence of changing climate variables.

2.4 Effect of extreme weather events on insect pests

There is a projection that climate change will increase the frequency of extreme weather events such as floods, storms and heavy winds (Easterling et al., 2000). These extreme weather events may eliminate vulnerable pest stages such as the eggs, larval and pupal stages, leading to breakdown of natural control, as many parasites and parasitoids will fail to find a host that is of a suitable developmental stage (Cork et al., 2014).

Increases in occurrence and severity of windy periods also occur as a result of a changing climate and results in increased insect pest incidence. For example, New Zealand has been exposed to airborne insect pests from Australia for millions of years (Cork et al., 2014). Higher wind conditions accompanied by high rainfall amounts, are therefore likely to result in distant spread of insect pests that are dispersed by wind and water currents. Wet vegetation resulting from heavy rainfall promotes the germination of spores and the proliferation of bacterial and fungal diseases within the crop canopies. Since most work was carried out in

Europe and Australia, the influence of altered precipitation regimes (rainfall) on insect pests and diseases need to be investigated from a tropical area perspective.

2.5 Effect of climate change on the activity of entomopathogens

Insect pests are indirectly affected by climate change as a result of the reduction in the efficacy of biological control by microbial entomopathogens. Microbial entomopathogens are microscopic, biotic organisms that are used for the control of insect pests. They include bacteria, viruses, fungi and nematodes (Veena et al., 2005). These are used to control insect pests by invading through the cuticle or the alimentary canal of an insect. This is followed by rapid multiplication of the pathogen within the host insect haemolymph thereby producing toxins which are dangerous to the insect pest. They reproduce within the insect pest by using nutrients present in the haemocoel to avoid insect immune responses (Burges, 1981; Meadows, 1993) resulting in mortality of the insects.

Bacteria such as *Bacillus thuringienis* (Bt) is mainly used for classical bio control and it constitutes almost 80% of the classical biocontrol. Approximately 20% of the classical biocontrol is caused by viruses mainly baculoviruses (Veena et al., 2005). Baculovirus has been used to control the velvet been caterpillar in soybean while *Bacillus thuringiensis* var. *kurstaki* (*Bt*) was found to be effective against foliage-feeding caterpillars (Meadows, 1993). Entomopathogenic fungi can also be useful and may be applied in the form of conidia or mycelium which sporulates after application. *Beauveria bassiana* fungus has been used against and have been found to be effective against several types of insect pests (Hajeck & Leger, 1994).

Since fungi, bacteria and viruses cannot control their internal temperature, their activity is influenced by the environmental conditions, heat, desiccation, or exposure to ultraviolet radiation reduces the effectiveness of several types of microbial insecticides (Regis et al., 2000). Temperature increases will extend the period of time that is available for reproduction, dissemination and evolution of fungi because of their ability to tolerate a wide range of temperature (Nurhyati, 2013). The strongest effects of temperature increase are believed to take place in tropical countries because tropical species have a narrow temperature growth range (Ghini et al., 2011) thereby rendering the entomopathogens vulnerable to very high temperatures. Optimum temperatures may increase the metabolic rates of fungal pathogens as well as the rate of infection (Thompson et al., 2010). This implies that fungus entomopathogens are more likely to survive under higher temperatures in temperate climates. However, bacteria entomopathogens are likely to be negatively affected by higher temperatures in the tropics thereby making them ineffective biological agents under a changing climate because of their lower temperature optima. In addition, since viruses rely on the availability of the hosts to survive, the increased incidence of insect pests under elevated temperature conditions also increase the activity of the viral entomopathogens. On the other hand, the availability of moisture affects prevalence of entomopathogens (bacteria, viruses and fungi). Higher moisture availability is likely to increase the rate of multiplication of fungi, viruses and bacteria while lower moisture availability is likely to render entomopathogens ineffective under dry environmental condition which are induced by droughts.

2.6 Impact of climate change on insect-plant interactions

Global climatic change affect insect pests through alterations in host plants morphology (Lake & Wade, 2009), biochemistry (Yuan et al., 2009), physiology (Yadugiri, 2010) species richness, diversity and abundance (Kazakis et al., 2007). These alterations have important implications for food security and the natural ecosystems (DeLucia et al., 2011).

Elevated atmospheric CO_2 affects plant-insect interactions through its direct effects on plants (Goyret et al., 2008). Elevated CO_2 typically increases the concentration of leaf carbohydrates and in combination with elevated temperature decreases nitrogen (N) content (Cornelissen, 2011). This dilutes the nitrogen in the plant leaves resulting in lower nutritional value of the plants. This in turn causes certain herbivores to consume more foliage to meet their nutritional needs (De Lucia et al., 2011). This leads to low growth rates of insect pest as a result of low nitrogen, longer developmental time and hence an increase in the window period of insect pest vulnerability to natural enemies resulting in higher insect mortality due to natural enemy attack (Petermann et al., 2010).

In a study in a meadow steppe, a three year field experiment was conducted to determine the potential responses of plant and insect communities, and plant-insect interactions, to elevated temperature. Warming increased the biomass of plant community of broad leaved plants, and decreased grass biomass. This resulted in lower abundance of insects community under warming, particularly the herbivorous insects as a result of lower abundance of *Euchorthippus unicolor* and a Cicadellidae species resulting from lower food availability and higher defensive herbivory (Zhu et al., 2015).

Drought indirectly affects the metabolic changes in the plant, such as increased levels of available sugars and essential amino acids, which according to the "Plant stress hypothesis" causes the plant to have a higher nutritional value for herbivores (White, 2009; Yuan, 2009). This can induce herbivore outbreaks (Guo et al., 2013; Johnson et al., 2014). On the other hand, drought is associated with a decrease in growth and an increase in plant defensive compounds making the plant less suitable for herbivores according to the "Plant Vigor Hypothesis" (Cornelissen, 2008). Excess precipitation such as hurricanes may influence the availability of light and nutrients for surviving trees thereby reducing the allocation of compounds to plant nutrition and defence. This, in turn negatively affect insect feeding and performance. Drought, thus have twofold influence on plant physiology through either concentrating nutrients within the plants or through the production of the defensive compounds that inhibit insect pest feeding. Research need to be conducted in various climatic conditions as well as on plants with differing physiology to determine the influence of drought conditions on the plants of differing physiology and environmental conditions.

2.7 Conclusion

From the review, we conclude that elevated temperatures, CO_2 and extreme weather events such as floods and storms have an effect on the rates of fecundity, development, survival, distribution as well as incidence of insect pests and diseases in a changing climate. Despite an expected increase in insects and diseases, some temperate insect pests as well as some diseases such as wheat stripe rust are expected to become less prevalent under a future climate in the temperate regions. Most of the researches on climate change were mainly conducted in the Asian, European and the temperate settings and limited information is available on the influence of climate change on polyphagous insects that are dominant in the tropical regions of Africa. Future researches should focus on the interaction between temperature and CO_2 on neglected pests and viral disease in the warmer tropical areas such as Southern Africa. Precipitation should also be considered in climate change studies because it is likely to directly and indirectly affect the distribution of tropical insect pest species. Location specific long term surveillance and monitoring of insect pests is also of importance in climate change studies as this will provide a more realistic assessment of climate change on insect pests and pathogen interaction.

Various models have been used to predict how global warming will affect insect ecosystems. Some of these models have been used to predict the response of individual insect pests to climate change. Future research should concentrate on models which are used to explore the response to climate change of various insects and pathogens in specific areas. Focus should be on modelling insects-climate change envelopes along with climate change. This would increase the capacity to forecast insect population and outcomes. Much research is needed on how modification in development of insects, host resistance phenology and physiology of host insect will occur from global warming.

Risk and hazard rating systems are essential components of crop health management strategy and should be in place and applied in advance of insect epidemics and outbreaks. These systems should be a priority for crop health research and development efforts. In addition climate mapping which predicts the potential distribution on insects in new areas under future climates should be part of the research to support the modelling exercises.

National and regional early warning and surveillance systems should be part of national policy to deal with increased pests and diseases under climate change. Most of the work on pests and diseases under climate change has been done in temperate regions. There is need for urgent research in the tropics of sub-Saharan Africa which have a low adaptive capacity to deal with the changing climate. These studies should be conducted on pests and diseases on a crop-forestry-livestock-human continuum.

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CHAPTER 3

RESPONSES OF INSECT PESTS TO A CHANGING AND VARIABLE CLIMATE IN ZIMBABWE: FARMER PERSPECTIVES

Rumbidzai Debra Chapoto[1, 2], Paramu Mafongoya[2], Augustine Gubba[2]

[1] Department of Agricultural Management, Zimbabwe Open University, Mashonaland West Region, P O Box 285, Chinhoyi, Zimbabwe

[2] School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa

Abstract

Climate change is likely to alter the abundance, behaviour and emergence of new insect species in Zimbabwe. This study was conducted in Zimbabwe to determine the perceptions of farmers to climate change and the resultant insect pest abundance, behavioural attributes, emergence of new insect species and the perceived causes of the changes in insect populations. Qualitative and quantitative research methods were used to solicit the data from the respondents in five districts representing the agro ecological regions also known as the natural regions (NR). Surveys, focus groups and key informant interviews were used for data collection. Twenty two percent of the farmers across natural regions perceived changes in climate to be increase in temperature throughout the year and increases in frequency of droughts. Late rainfall was cited by 16.4% of the farmers while long dry spells was cited by 16% of the respondents and 7.2% cited shorter cold season as the major indicator of a changing climate. Increasing incidence of heat waves, flash floods and the disappearance of wetlands and green spaces were cited as other indicators of a changing climate. Increased abundance of insect pests, decreased natural resource base and reduction in social safety nets were perceived to be the major climate change risks that were experienced by the smallholder farmers. The majority of the farmers (89%) have also expressed experiencing an increase in the incidence of insect pests such as aphids, stem borers, termites, diamond back moths, bollworms and whiteflies throughout the agro ecological regions of the country. Four percent perceived a decrease in insect pest incidence while 1% was not sure whether insect pests were increasing or decreasing. Farmers also perceived a change in behaviour of insects such as an increase in mobility as cited by 50.8%[1]and colour variations within insect species as highlighted by 73.6% while 59% perceived an emergence of new insect pests. The increase in pest problem was perceived by the farmers to be caused by changes in weather patterns such as elevated temperatures throughout the year and increased dry spells. Research on management strategies to cope with an increasing insect pest population in a changing climate is of importance in future studies.

Keywords: climate variables, insect abundance, perceptions.

[1] Chapter 2 was submitted to Climatic Change journal

3.1 Introduction

Climate variability and change are resulting in changes in global weather patterns (Selvaraj & Pandiara, 2013). The weather variables that are altered as a result of a changing climate include rainfall, temperature, atmospheric gas composition, wind and cloud cover. However, temperature is one variable that is known to cause significant observable effects to the farmers (Bale & Hayward, 2010). The atmospheric warming resulting from elevated temperatures is threatening to influence various human economic activities mainly agriculture in both developed and developing countries (Jiri et al., 2015; Sahu, 2013). The effects of shifting weather patterns are more acute in the developing countries including the Sub-Saharan region than the developed world (Rurinda et al., 2014). However, the southern African region is particularly most affected by a changing climate because of widespread poverty (Mapfumo et al., 2013), recurrent droughts, unfair land distribution, over-reliance on rain-fed agriculture (Comoe & Siergist, 2015) and low capacity to adapt to the changes in the weather patterns (IPCC, 2014).

Current estimates of global changes in climate indicate an increase in mean annual temperatures of 3°C by the end of the 21st century (IPCC, 2013). In Zimbabwe, by 2050, mean annual temperatures are projected to increase by 2-4°C, while rainfall is expected to decrease by 10-20%, which is significantly lower compared to the 1961-1990 baselines (Unganai, 2006; Lobell, 2008). By the year 2080, annual rainfall averages are projected to be lower than the 1961-1990 averages by 5-18% (Lobell, 2008).

The changing and variable climate is likely to increase susceptibility of farmers in the developing countries to yield loss and hence food insecurity as a result of insect pests surges (Fand et al., 2012, Selvaraj, 2013). Climate change has an effect on crop insect pests and diseases beyond the effect of the weather variables themselves (Ma & Ma, 2012a). In Zimbabwe, the agriculture sector is the backbone of the economy. It plays a significant role in the economic, social and political lives of the majority of Zimbabweans (Maiyaki, 2010). Smallholder farmers are vulnerable to the adverse impacts of the changing climate because of various factors such as poor soil fertility (Mapfumo and Giller, 2001), high population pressure (Frost et al., 2007), higher levels of poverty (Mapfumo et al., 2013) and over reliance on rain fed agriculture (Maiyaki, 2010).

In Zimbabwe, research has been carried out to determine the vulnerability of the agricultural system to weather variables (Mapfumo et al., 2013). Very few studies have focused on the vulnerability of agricultural system as influenced by insect pests and diseases in a changing climate. There is thus a gap in assessing smallholder farmer's perceptions on insect pests and diseases (Adam et al., 2015). The perceptions will affect how farmers will adapt and mitigate against climate driven insect pest risks. This study therefore aimed to determine the perceptions of farmers with respect to climate change in Zimbabwe, indicators of climate change and variability, climate change risks to crop production, changes in behaviour and physical traits of insects as well as farmers' perceptions on the causes of changes in insect pests' dynamics.

3.2 Materials and methods

3.2.1 Description of the study area

Zimbabwe is divided into five agro-ecological regions also known as Natural regions (NR) based on the rainfall regimes, soil quality and temperatures (Vincent & Thomas, 1960). The study was carried out in the different agro ecological regions of the country (Fig 3.1). These agro ecological regions are also known natural Regions (NR) based on mean annual rainfall, soil quality and mean annual temperature regimes (Vincent & Thomas, 1960). The five regions were considered in this study based on their contribution to agricultural production mainly at smallholder production level. The country has a wide spatial and temporal variation in rainfall and temperature. Mean annual rainfall and the quality of land resources declines from NR1 to NR5 whereby rainfall amounts range from as high as over 1000mm in NR1, 750-1000mm in NR2, 650-750mm in NR3, 450-650mm in NR4, and less than 450mm in NR5. The mean maximum and minimum temperature ranges decline from NR1 to NR5. Mean maximum temperature ranges from 23˚C in NR1 to 32˚C in NR5. During the winter season mean minimum temperature ranges from 10-12˚C in NR1, 10-13˚C in NR2, and 14-15˚C in NR3, 11-18˚C in NR4 and 14-20˚C in NR5. The quality of the soils decline from NR1 to NR5 (Anderson et al., 1993; Vincent & Thomas, 1960).

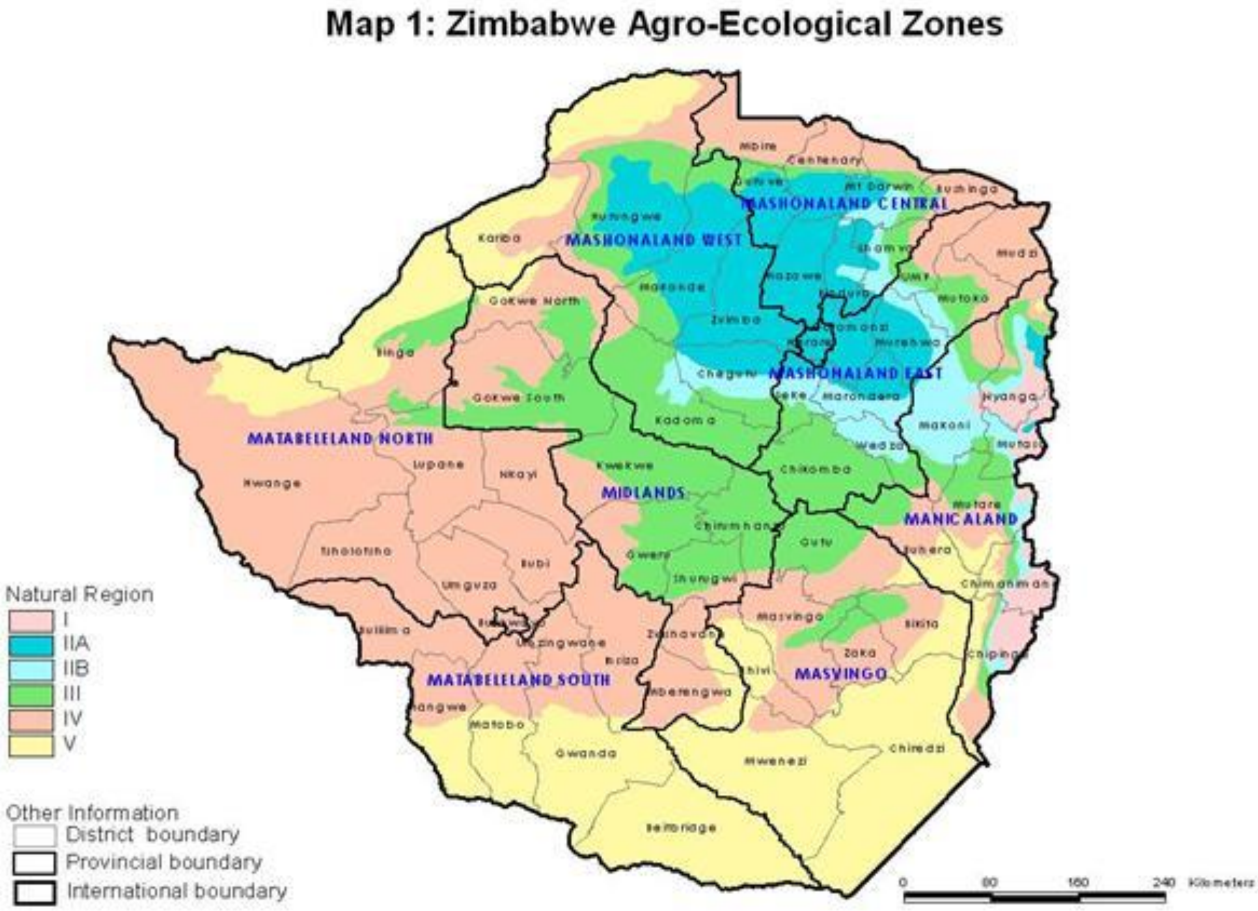

Fig 3.1: The five agro ecological regions of Zimbabwe.
Adapted from FAO (2009).

3.2.2 Data collection and analysis

This research used the concepts of perceptions on evaluating farmers' perceptions on the responses of insect pests to a changing climate (Adam et al., 2015; Khan et al., 2014, 2015; Lagerkvist et al., 2012). Farmer perceptions helps us to know what farmers think and feel about a changing climate, the corresponding insect pests problem, behavioural and morphological attributes or changes in the physical appearance of the insect pests in the various agro ecological regions of the country.

The study employed both the quantitative and the qualitative research approaches (Bryman, 2004). Quantitative information was collected through a detailed survey using semi structured questionnaire. Primary data collection was a three stage process. At both the first stage and second stages farmers were systematically sampled from each district representing an agro ecological region. That is, in each district, two wards composed of smallholder farmers (with landholding of less than 6ha) were sampled based on farmers who had stayed in the area for at least 30 years as well as from the lists of farmers who have been perceived by the district agriculture extension officer as productive. From each ward, 25 farmers who were active in the production of agricultural crops were randomly selected. The different NR were used in this study in order to obtain a wide range of farmer perceptions.

3.2.3 Qualitative data collection

Qualitative data was collected through in-depth discussions with focus group participants at meetings that were organised at each of the site representing an agro ecological region. Key informant interviews with the agriculture extension officers, traditional leaders and Environmental Management Authority (EMA) were conducted to augment and compare farmer responses from the questionnaire survey.

3.2.4 Statistical tests for data reliability

Primary data analysis was done by firstly coding household survey data in Excel. The data was then transferred to Statistical Package for Social Sciences (SPSS) package version 16 for statistical data analysis. Data was subjected to analysis of variance at $p<0.05$. In instances were a significant difference was noted, a *post hoc* analysis was conducted to determine the agro ecological region showing significant differences. In addition, problem ranking matrices were also used in the study.

3.3 Results

3.3.1 Farmer perceptions and understanding of climate change

Across all the agro ecological regions, the majority of the farmers (84%) perceived a change in climate, 6% were not aware of a changing climate while 10% were not sure whether the climate was really changing or not in the past 30 years. There was no significant difference in farmers perceptions about climate change by the respondents in NR1, NR2, NR3 and NR4 at $P<0.01$, where the majority of the farmers in these 4 regions perceived a change in climate. However, a higher proportion of farmers in NR5 were either not aware or not sure of a changing climate and their perceptions on climate change was highly significantly different ($p<0.01$) from the farmers in the other 4 NR (Table 3.1).

Table 3.1: Farmer perceptions to climate change and variability (% responses; N=250).

Climate change awareness	NR1	NR2	NR3	NR4	NR5	Mean	P-value
Aware	100	100	100	88	32	84	0.00*
Not aware	0	0	0	0	28	6	0.00*
Not sure	0	0	0	12	40	10	0.00*
Total	100	100	100	100	100	100	0.00*

NB: P≤05, there is a significant difference, * significant at p<0.01

The majority (22%) of the total respondents across the five agro ecological regions perceived an increase in the temperature and increased frequencies of droughts to be the major indicators of a changing and variable climate. Respondents also perceived changes in climate to be change in duration of rainfall season duration, distribution, amounts, onset of the rainy season as well as shorter cold seasons. From these results, there were no significant differences (P=0.983) on the perceived indicators of climate change across the 5 agro ecological regions (Table 3.2).

Farmers' perceptions of changing climate conditions such as increasing temperatures and increased frequencies of droughts were however in line with the scientific observation of climate data. The time series for Zimbabwe indicates numerous years that received below normal rainfall (Figure 3.2), variable rainfall (Figure 3.3) and a positive trend in the minimum and maximum temperatures (Fig 3.4). This implies that the country is becoming more prone to droughts, variable rainfall and increased temperatures respectively.

Table 3.2: Farmer perceptions of major indicators of climate change and variability in Zimbabwe (% responses; N=250).

Indicators of climate change	NR1	NR2	NR3	NR4	NR5	Mean	P-value
Late rainfall	16	16	18	16	16	16.4	NS
Long dry spells	14	16	18	16	16	16	NS
Higher frequency of droughts	20	22	26	20	22	22	NS
Shorter cold season	10	12	2	6	6	7.2	NS
Increased frequency of floods	20	10	12	22	18	16.4	NS
Increased temperatures	20	24	24	20	22	22	NS
Total	100	100	100	100	100	100	

NB: P>0.05, there is no significant difference, NS-Not significant at $p<0.05$, figures in the text refer to percentage of farmers

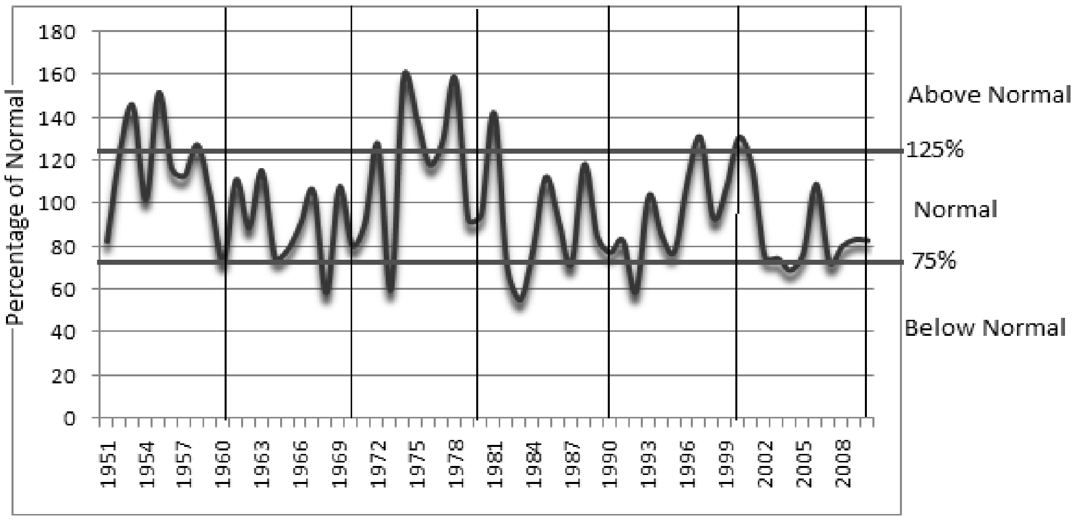

Fig 3.2: Time series showing the extreme rainfall years (flood) and below normal rainfall (drought periods) in Zimbabwe.

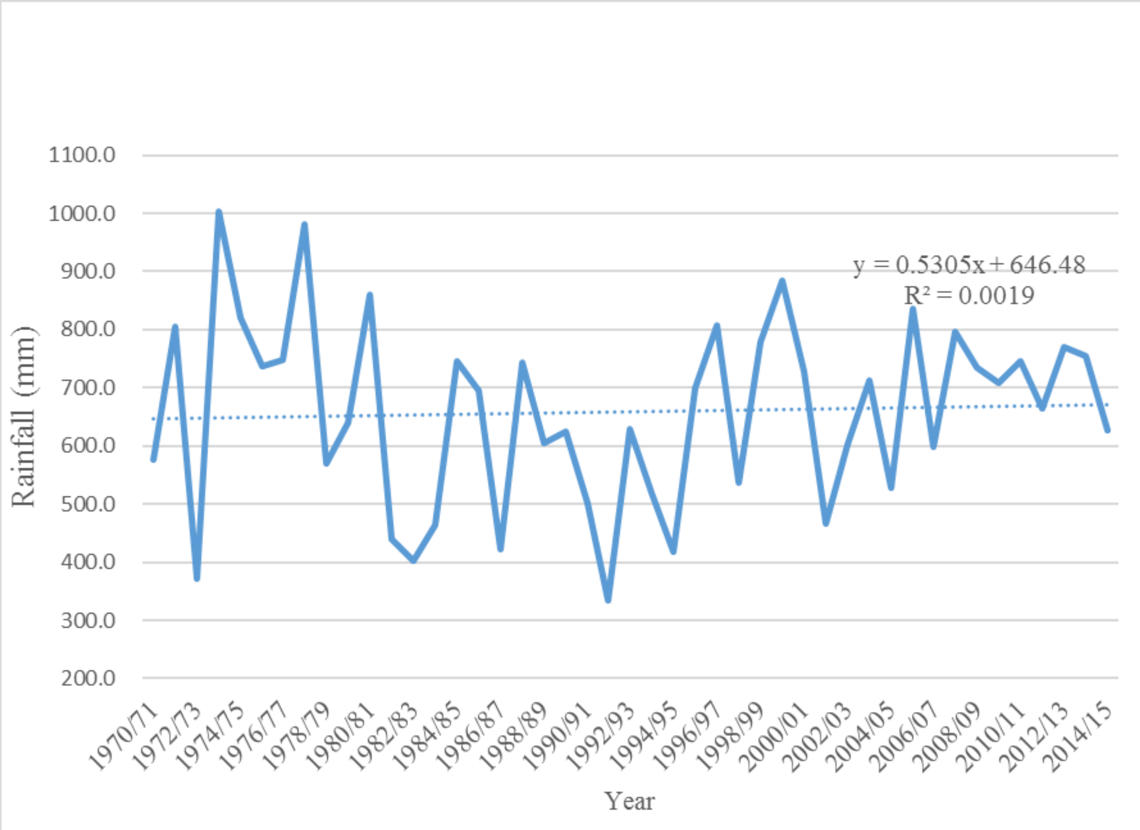

Fig 3.3: Trend analysis showing rainfall variability in Zimbabwe.

Source: Zimbabwe Meteorological Services Department (2016)

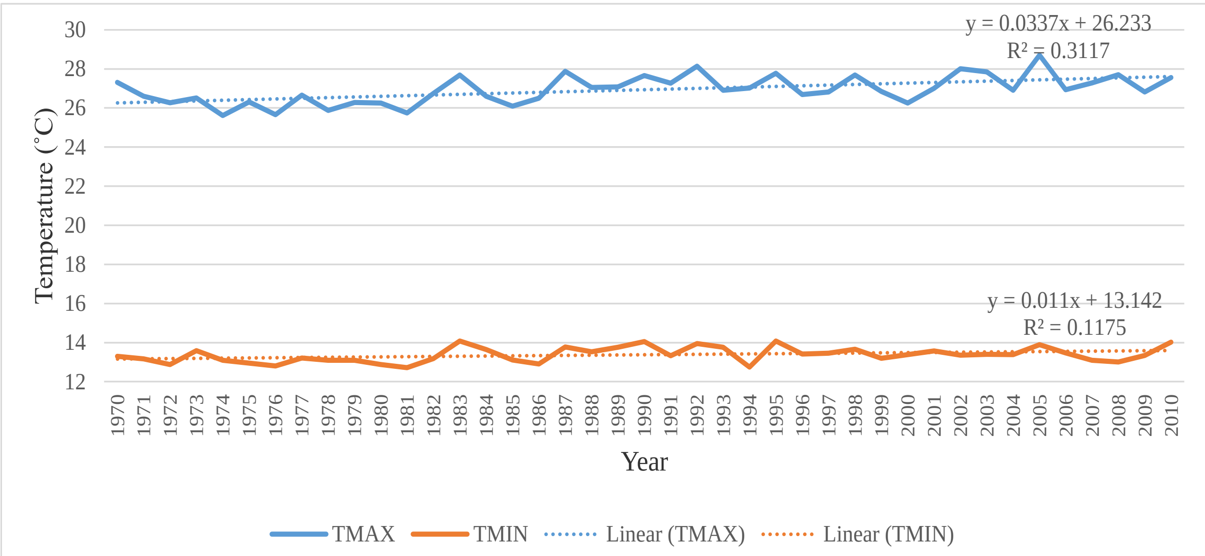

Fig 3.4: Trends in minimum and maximum temperatures.

Source: Zimbabwe Meteorological Services Department (2016)

The recall of weather and climatic conditions through in depth interviews with extension officers, traditional leaders as well as the focus group discussions also showed a close relationship with the climatic records. The respondents in all the agro ecological regions highlighted that they have experienced uneven rainfall distribution which manifests itself sometimes as excessive rainfall, although there may not be any flooding. The excessive rains were said to be accompanied by violent winds and heavy storms then prolonged dry periods would follow immediately after the heavy rains. During the year 2000 and 2003, the focus group discussants in most parts of the country especially NR1, NR2, NR3 as well as the key informants recalled the occurrence of the tropical cyclones "Eline" and "Japhet" respectively, which destroyed most of their crops, vegetation and property due to the vicious winds and hailstorms that were associated with the weather events. In the 2008/9 agricultural season, farmers also experienced excessive rains leading to flooding in all the natural regions and the excessive rainy periods were in most cases followed by a drought season. This corroborated the time series analysis for Zimbabwe which indicates that the last two decades 1990-2010 had more years in the drought category than other decades (Figure 3.1). The farmers also cited the heavy rainfall that was experienced in all the agro ecological regions in the 2014/2015 rainy season which led to flash floods in all the agro ecological regions. The rains were said to be confined to the first week of January 2015 and they cited that a dry spell was experienced soon after the heavy rains. The EMA officers and the local leaders were also worried by the disappearance of green spaces as well as the wetlands in all the agro ecological regions of the country which they attributed to the changes in the climate conditions.

3.3.2 Farmer perceptions of climate change and variability induced risks in Zimbabwe

The perceived climate change risks to crop production were mainly as a result of changes in temperature and rainfall (patterns, amounts and intensity) as well as increased frequency of droughts. These changes in weather events were perceived to affect crop production directly through a reduction in crop productivity and indirectly through changes in the quality and quantity of natural resources. Changes in temperature and rainfall patterns were perceived to alter the distribution of natural resources such as trees, desirable vegetation (trees and grasses) as well as water resources leading to a corresponding increase in the incidence of crop pests (weeds, insects, diseases). Pest outbreaks resulted in crop failure leading to farmers competing for natural resources (such as wild fruits) with wild animals (Table 3.3).

Table 3.3: Farmer perceptions of climate change risks and impacts that are caused by changes and variability in climate.

Climate risk	Affected subsystem	Main subsystem Affected	Positive impacts	Negative Impacts
Increased Rainfall Variability	1.Crop production	Crop yield	Increase in crop yields on elevated ground and wetlands	Loss of soil due to water logging and leaching
	2. Natural resources (trees, land, water)	Fruits Trees for botanicals Decline in mulching materials	_	Reduced availability of fruits
	3. Labour availability	Loss of hired labour for pest management due to emigration	_	Increase abundance of Insects Crop disease Outbreak
Temperature Extremes	1. Natural resources (trees, land, water)	Reduction of fruits and mushroom Reduced mulching	_	Reduced off farm food
	2. Labour availability	Reduced labour for pest management	_	Increased insects pests Crop Diseases Outbreak
	3. Crop production	Crop yield	_	Crop failure
Droughts	1.Crop production 2. Natural resources (trees, land water)	Crop yield Reduction of fruits mushroom, trees for shade and poles Reduction in mulching material	_	Crop failure Reduced fruits
	3. Labour availability	Labour for pest Management	_	Increase incidence of insects pests and crop Diseases Outbreak

Source (Focus Group Discussions, 2015).

Table 3.4: Ranking of major insect pests of agricultural crops as perceived by the smallholder farmers in order of importance where (1 is the most important) (% responses; N=250).

Ranking	NR1	%	NR2	%	NR3	%	NR4	%	NR5	%
1	Aphids	26	Aphids	32	Bollworms	40	Termites	34	Termites	36
2	Stem borer	22	DBM	24	Aphids	26	Aphids	22	Stem borer	20
3	Cutworms	20	Stem borer	18	DBM	14	Whiteflies	16	DBM	18
4	Whiteflies	18	Cutworms	14	Cutworms	12	Stem borer	16	Aphids	14
5	Leaf miners	14	Bollworms	12	Stem borer	8	Cutworms	12	Bollworms	12
Total	Total	100		100		100		100		100

Notes: DBM-Diamond Back Moth

Source (Survey data, 2015)

Insects such as aphids, stem borers, bollworms, diamond back moth (DBM), cutworms, termites, whiteflies and leaf miners were found to be key pests in the various NR of the country. Aphids and the stem borers were perceived as the dominant insect pests in all the agro ecological regions. Bollworms were identified as the key pest in NR3 and termites were more dominant in NR4 and NR5 (Table 3.4). In depth interviews with extension officers highlighted that aphids and the diamond back moths are more prevalent in winter in NR4 and NR5, and an increase in the population of these pests throughout the year in NR1, NR2 and NR3.

Table 3.5: Ranking of major crops produced in the various agro ecological regions (where 1 is the most widely grown and 5 is the least widely grown).

Ranking	NR1	NR2	NR3	NR4	NR5
1	Fruits	Maize	Cotton	Maize	Sugarcane
2	Maize	Tobacco	Maize	Millet	Millet
3	Cabbages	Tomatoes	Tomatoes	Cabbages	Maize
4	Tomatoes	Cabbages	Tobacco	Cotton	Vegetables
5	Yams	Rape	Cabbages	Roundnuts	Rapoko

Source: (Data from the FGDs, 2015)

3.3.3 Major crops produced in the various agro ecological regions

The most widely produced crop is maize across all the agro ecological regions. Fruits were highlighted to be major crops in NR1 while in the other NR they are not of major importance. Small grains were also identified as major crops produced in the lowveld areas of the country which cover NR4 and NR5. These small grains were not common in NR1, NR2 and NR3 (Table 3.5).

3.3.4 Perceived changes in insect pest incidence and emergence of new insect pest

The study revealed that across the five NRs, the majority (89%) had the perception that insect pest incidence was increasing in the last 30 years while 4% perceived a decrease in insect incidence and 1% was not sure of the status of insects over the past 30 years. There was however no significant difference in farmer responses between the 5NR at $p<0.05$ where the majority of the respondents had the perceptions that the incidence of insect pests has been increasing. On the perceived emergence of new insect pests, there was a significant difference in the response of farmers at p<0.01. The results indicated that there were no significant differences in farmers' responses between NR1, NR2 and NR3. However, there was a significant difference in farmers' perceptions to emergence of new insect pests between farmers in NR2 and those in (NR4 and NR5) where the majority of farmers in NR2 strongly agreed that there is an emergence of new insect pests while fewer farmers in NR4 and NR5 strongly agreed (Table 3.6). The key informants also highlighted an increase in insect pest incidence as well as the emergence of new insect pests in all the agro ecological regions.

3.3.5 Perceived behavioural and physical attributes of insect pests in a changing climate

Increased insect pest movements and a rapid reproduction rate were the main insect behavioural attributes that were noted by the respondents. Of the total respondents, 50.8% cited an increase in insect pest movement on infested plants while 49.2% cited an increase in the reproductive rates of insect pests. However, there was no significance difference (P>0.05) between the respondents in the five NRs regarding the behaviour of the insect pests (Table 3.7). Across the 5NRs, 73.6% perceived that insects are developing different colour variations while 26.4% have observed an increase in the population of winged insect types compared to the same types of insect pests in the past 20 years. However the responses of the farmers on the physical appearance were not significantly different from each other at P<0.05 (Table 3.7). In all the agro ecological regions, the key informants noted changes to the behaviour and the physical appearance of insect pests over the past years.

Table 3.6: Farmer perceptions of changes in pest incidence and emergence of new insect pests (% responses; N=250).

Variable	NR1	NR2	NR3	NR4	NR5	Mean	P-value
Perceived changes in population							
Increased	98	96	90	84	76	89	NS
Decreased	0	0	0	8	12	4	NS
Not changed	2	4	8	6	10	6	NS
Not sure	0	0	2	2	2	1	NS
Total	100	100	100	100	100	100	
Perceived emergence of new insects							
Strongly agree	40	52	42	24	26	37	0.006*
Agree	58	48	54	70	66	59	0.006*
Disagree	2	0	4	6	8	4	0.006*
Total	100	100	100	100	100	100	

NB: $P \leq 0.05$, there is a significant difference, * significant at $p<0.01$, NS-Not significant at $p<0.05$

Table 3.7: Perceived changes to behaviour and physical appearance of insect pests (% responses; N=250).

Variable	NR1	NR2	NR3	NR4	NR5	Mean	P-value
Behavioural attributes							
Increased insects movement	56	56	48	44	50	50.8	NS
Fast reproduction rates	44	44	52	56	50	49.2	NS
Total	100	100	100	100	100	100	NS
Physical appearance							
Colour variations	78	66	70	74	80	73.6	NS
Increase in winged insects	22	34	30	26	20	26.4	NS
Total	100	100	100	100	100	100	

NB: $P>0.05$, there is no significant difference, NS-Not significant at $p<0.05$

The respondents perceived shorter winters, high temperatures and increased length of the dry spell as the major factors underlying increased insect pest prevalence in the various regions of the country. There was a highly significant difference (P=0.00) across the agro ecological regions on the perceived causes of the insect pest risk in a changing climate. There was no significant difference in farmer perceptions in NR2, NR3 and NR4, but significant differences were noted between farmer responses in NR 1 and those in NR5 where the majority (46%) of the respondents in NR1 cited shorter winters as the major causes of increased insect pest prevalence while farmers in NR5 did not perceive any change in the length of the winter season (Table 3.8).

Table 3.8: Perceived major causes of the increased prevalence of insect species in the various agro-ecological regions of Zimbabwe (% responses; N=250).

Variable	NR1	NR2	NR3	NR4	NR5	Mean	P-value
Perceived cause of insect pest risk							
Shorter winters	46	28	44	26	0	28.8	0.00*
High temperatures	26	44	22	42	20	30.8	0.00*
Increased dry spell	28	28	34	32	80	40.4	0.00*
Total	100	100	100	100	100	100	

NB: $P \leq 0.05$, there is a significant difference, * significant at $p<0.01$

3.4 Discussion

The increase in awareness to climate change by the majority of the respondents were related to the studies that were conducted in Ethiopia (Legesse et al., 2013), Nigeria (Tambo & Abdoulaye, 2013) and Chile (Roco et al., 2014). The results also concur with meteorological data which showed that the frequency of drought events have increased with most of the drought events taking place between the year 2000 (Meteorological Services Department (MSD, 2013). It is during the 1991-1992 season when the most devastating drought occurred in Zimbabwe (Manatsa et al., 2008). The majority of farmers in the arid regions (NR4 and NR5) however did not notice a clear distinction in the change in climate over the past years probably as a result of being accustomed to the already harsh weather variables that were experienced in these areas (Mubaya, 2010).

Perceived crop production risks associated with a changing climate such as increased insect abundance were in line with the work of Arbuckle et al. (2013); Safi et al. (2012); Le Dang et al. (2014) who indicated that the farmers who are aware of climate change are also aware of the risks that are associated with a changing climate such as the increase in the abundance of crop pests and the corresponding yield reduction.

A perceived increase in the prevalence of insect pests, such as aphids and bollworms across the NRs could have been as a result of the polyphagous feeding habit of these insects and high reproductive rates in a changing climate (Hazell et al., 2010; Sharma et al., 2011). In a study that was carried out in Botswana where climate was simulated, it was shown that aphid populations increased quickly on infested cabbage plants because of rapid multiplication rates which prevailed at elevated temperature conditions (Munthali & Tshegofatso, 2014). There are also indications that as a result of the polyphagous nature of aphids, they may become key pests of a number of crops in the future as a result of climate warming (Selvaraj, 2013).

The presence of cereal crops which include the staple (maize) crop in Zimbabwe and the ability of stem borer to inhabit wild grassy hosts could also have led to its increased incidence across the country's natural regions (Calatayud et al., 2014). In NR4 and NR5 the higher prevalence of stem borers could have resulted from the cultivation of a variety of drought tolerant cereals such as sorghum, rapoko and millet. In addition, sugarcane production in the Save and Runde river catchment area which is part of NR4 and NR5 could also have led to the incidence of this insect pest in the drier and hotter agro ecological regions of the country. In an insect pest distribution survey conducted in Togo, stem borers were found in all the agro ecological zones where cereals are grown (Tounou et al., 2013). Stem borers have thus been classified as the major pest behind reduced cereal yields in East Africa as a result of the outbreak resulting from rainfall variability in the region (Midega et al., 2015). This therefore implies that with increased climate and hence rainfall variability, stem borers will become major insect pest in the future wherever cereal crops are cultivated.

In some surveys, an increase in termites was reported during mid-season drought periods on agricultural lands (Kladivko, 2008). In an experiment conducted in some agricultural lands, the activities of termites were found to be influenced by soil moisture where low densities of the termites were observed in high rainfall areas as well as wetlands while higher densities were observed in more arid areas (Nhamo, 2007).

Brassica crops, the specific hosts of DBM are widely distributed throughout the country because of their contribution to income and food security among the smallholder farmers (Dosdal et al., 2011). This was likely to cause a high prevalence of DBM in all the NR of the country. In addition, diamond back moth has a huge reproductive potential, ability to cope with environmental changes thereby enabling it to rapidly increase its population in a changing climate in all the agro ecological regions (Furlong et al., 2013). Diamond back moth is also highly mobile such that it can also travel large distances to new cruciferous crops thereby increasing their spatial distribution in all the places where cruciferous plants are grown (Selvaraj & Pandiara, 2013).

This study showed evidence that insects could become mobile as a result of elevated temperature conditions. This is because the insects avoid heat injury by moving from the top leaves to the understorey leaves which protect them from temperatures extremes in the upper storey of the crops (Ma & Ma, 2012a). Some laboratory studies that were conducted indicated that some aphid species were more mobile under heat stress as they attempted to escape from potential heat injuries compared to those that were exposed to optimum or lower temperature conditions (Ma & Ma, 2012b).

Increased appearance of winged morphs in pests such as aphids in response to changes in environmental factors is also of importance in aiding migration and colonisation of new host plants or habitats after predicting potential heat injury and also as a result of overpopulation (Brisson, 2010; Ma & Ma, 2012a). The colour changes on some insect species could have been as a result of polymorphism under changing weather conditions (Tsuchida et al., 2010). In an experiment that was conducted on tobacco aphid in Zimbabwe, the red morph took a significantly shorter time to produce its first offspring and also produced a significantly higher number of total nymphs and number of nymphs per day than its green counterpart (Masukwedza et al., 2013). This enable the adaptive insect morphs to maintain a high reproductive rate and a corresponding high population under high temperature conditions.

The emergence of new insect pests as perceived by the respondents could have been due to the introduction of new crop varieties as a way of adapting to extreme temperatures and rainfall variability by the farmers (Gregory et al., 2009). Studies carried out by Fahim et al. (2013), Comoe & Siergist, (2015) and Menapace et al. (2015) showed that climate change will alter the distribution, incidence and intensity of plant pests and diseases and cause new crop pests and diseases to emerge.

In a changing climate, increased dry spells or drought conditions have been found to cause surges in disease, insects and weed pressure on crops (Niang et al., 2014). In a study where physical control of aphids was practised, it was found that aphid populations on sturdy plants were dislodged with a strong spray of water (Barbercheck, 2014). This implies that more frequent and extreme rainfall may expose the insect pests to dislodging from the plants, therefore reducing insect population under heavy precipitation unlike in dry weather conditions, light rainfall or moderate rainfall conditions where the insects' pests will remain attached to the host plants.

3.5 Conclusion

The study revealed that smallholder farmers have perceived a changing climate to be increasing temperatures, increased frequencies of drought events resulting in an increase in insect pest populations. The farmer's perceptions were in accordance with the recorded meteorological data where a variable trend in rainfall and a positive trend in annual minimum and maximum temperatures over the past years have been observed. According to farmers, an increase in the abundance of various insect pests such as stem borers, aphids, termites and diamond back moths has been observed across the NR although in NR4 and NR5 these insects were perceived to be more abundant during the winter season. The farmers perceived an increased occurrence of new and unknown insect species. The increased prevalence of the insects was perceived to be caused by changing weather variables as a result of changing climate. Baseline field surveys need to be conducted to verify farmers' perceptions. There is also need to carry out further research on adaptive strategies by the smallholder farmers so as to cope with changes in insect pest populations in an environment of changing climate. The strategies need to focus on vegetable crops because of their widespread production across the country, contribution to income, household food security and nutrition.

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CHAPTER 4

FARMER KNOWLEDGE OF CLIMATE CHANGE IMPACTS AND ADAPTATION STRATEGIES IN THE MANAGEMENT OF VEGETABLE INSECT PESTS IN ZIMBABWE

Rumbidzai Debra Chapoto[1, 2], Paramu Mafongoya[2], Augustine Gubba[2]

[1]Department of Agricultural Management, Zimbabwe Open University, Mashonaland West Region, P O Box 285, Chinhoyi, Zimbabwe

[2] School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa

Abstract

Farmer knowledge of insect pests' risks is of importance in the management of increasing insect pests' abundance in a changing and variable climate. A total of 250 vegetable farmers sampled from the five districts of Zimbabwe were interviewed using a survey questionnaire to assess their knowledge on changing climate variables, its impact on vegetable insect pests and the adaptation strategies to manage the challenges of increased abundance of insect pests. Focus group discussions, key informant interviews and field observations were also used in this study. The survey results revealed that droughts and elevated temperatures had the greatest impact on vegetable insect pests resulting in increased abundance of vegetable insect pests. Aphids, cutworms and whiteflies were identified among the major pests that have increased in abundance during the past 20 years across the agro ecological regions of the country. The majority (53%) of the farmers cited high vegetable losses from insect pests and diseases. All the respondents (100%) cited the use of chemical insecticides at some point during the production cycle of vegetables. A higher proportion (60%) perceived effective control of insects by chemical insecticides while 34% perceived reduced efficacy of the chemical insecticides and 6% were not sure of effectiveness of chemical insecticides. Management strategies to cope with the increasing insect pests and diseases on vegetable production included planting insect and disease resistant vegetable [2]cultivars, use of certified seeds, increased frequency of application of synthetic insecticides, using insecticide mixtures, use of more hazardous chemical insecticides as well as increasing the rates of application resulting in insecticide overuse. There is need for the government to facilitate the development and adoption of Integrated Insect Pest Management (IIPM) and raise awareness on avoiding overdependence on chemical insecticides. Insect pest modelling tools that support adaptation planning also need to be developed to forecast climate change events and the resultant abundance of insect pests and diseases.

Keywords: farmers' knowledge, insecticide overuse, elevated temperatures

[2] Chapter 4 is currently under review in International Journal of Pest management

4.1 Introduction

Climate change and variability has caused devastating effects in both developing and developed countries of the world (IPCC, 2014). Zimbabwe is one of the countries in the Sub Saharan region that is prone to the adverse effects of climate change, with predicted increases in mean temperatures and rainfall variability, and an expected increase in extreme weather events such as droughts and flash floods (Rurinda et al., 2014). According to the Zimbabwe Meteorological Services Department, daily minimum and maximum temperatures have risen by more than 2°C over the last century (Brown et al., 2012). Climate records show that temperatures have been increasing by around 0.1°C a decade and future scenarios predict increasing temperatures of around 2.5°C by the year 2050 (Government of Zimbabwe, 2013). Smallholder farmers in Zimbabwe are vulnerable to the impacts of a changing climate because of multiple factors, such as soil degradation (Rufino et al., 2013) extreme poverty and deterioration of societal 'safety nets' (Antwi-Agyei et al., 2012; Mapfumo et al., 2013). A dwindling natural resource base (Mapfumo et al., 2013; Rufino et al., 2013) and over dependence on rain fed agriculture (IFAD, 2010) have also increased farmers' vulnerability to the impacts of a changing climate.

Climate change affects crop yields and hence food security both directly and indirectly (Lobell, 2012). Food security is affected directly through yield losses due to adverse environmental conditions (Mapfumo et al., 2013) and indirectly through the changes to the population dynamics and geographic distributions of crop pests (Khan et al., 2014). Insect pest attack results in crop losses of about 13.6% of global agricultural production (Dhaliwal et al., 2010). In Zimbabwe, several studies have been conducted linking climate change with farmer vulnerability (Moyo et al., 2012; Mtambanengwe et al., 2012; Mucharia, 2012) but have not incorporated farmer knowledge on vegetable yield and farmer adaptation to insect pest problems considering the importance of vegetable crops nutritionally and economically. Most of the vegetable crops are grown in agro-ecological zones which are different from their regions of origin, therefore they are more susceptible to adverse bioclimatic factors and the associated losses (Singh & Singh, 2013). There is thus a gap in assessing smallholder farmer's knowledge and adaptive strategies in the management of insect pests under a changing climate (Adam et al., 2015).

An understanding of the farmer's knowledge of climate risk is important because it is a prerequisite for adaptation strategies that can be employed to reduce vulnerability to climate change (Sarr et al., 2015). Adaptation measures are of critical importance because the weather patterns have already changed and the changes are expected to continue even if mitigation measures are immediately put into place (Cobon et al., 2009). Without adaptation strategies, effects of climate can be devastating to the agricultural sector, but with adaptation, vulnerability can be greatly reduced (Jiri et al., 2015). Farmers' knowledge and management practices may therefore provide essential information for successful development of future insect pest management strategies (Kihupi et al., 2015).

This study focused on the concepts of knowledge and practices, which have been previously used in some studies in developing countries (Adam et al., 2015; Khan et al., 2015). Since adaptation is key for improving food security in the face of a changing and variable climate (Kihupi et al., 2015; Ramirez-Villegas & Thornton, 2015), there is need to identify adaptation strategies in the management of insect pests by the smallholder farmers which helps them to maintain higher levels of food security despite a changing climate and the associated insect pest risks. The research will be of importance in identifying sustainable solutions to agricultural production constraints by incorporating farmer views into research for development of food security programmes (Okonya et al., 2013). It is against this background that the aim of this study was to examine smallholder farmers' knowledge with regard to insect pests of vegetables in a changing climate and the adjustments made by farmers to manage the increasing insect pest problem.

4.2 Materials and Methods

4.2.1 Study area and the survey design

The study was conducted in five areas which represent five different agro ecological regions (Vincent and Thomas, 1960). The ward which was perceived to produce most vegetables in each NR was then selected for the purpose of this research. The wards were Gwayagwaya ward in Chipinge district (1118 metres above sea level, masl), Munyawiri ward in Goromonzi district (1515 masl), Mawanga ward in Mutoko district (1168 masl), Zimuto ward in Masvingo district (1166 masl) and lastly Chilonga ward in Chiredzi district (485 masl).

Multi stage systematic sampling procedure was used to come up with the respondents of the study. Three stages were used during selection. In the first stage, a list of wards participating in vegetable production in each agro ecological region were considered in the selection of the study sample. In the second stage, one ward and 5 villages within the ward that were easily accessible but found within a defined agro ecological region were randomly selected. In the final stage, 10 households were randomly selected from each of the 5 villages for the purpose of this study.

Pretesting of the questionnaire was done to perfect techniques of data collection. Appropriate adjustments were carried out to the questionnaire to perfect techniques of data collection. Appropriate adjustments were carried out to the questionnaire after the pretesting exercise.

This research study thus employed a mixed methods approach where individual farmers in selected households were the principal units of observation. Mixed methods integrate both quantitative and qualitative research techniques, into a single study therefore enabling a deeper understanding of the subject (Johnson & Onwuegbuzie, 2004). Data collection was also accomplished using focus group discussions and field observations. A survey data set containing detailed quantitative data from 250 households from the five agro-ecological regions of Zimbabwe was used. The respondents were purposely selected based on merit of vegetable production as perceived by the district agriculture extension officers. In addition, to high productivity, also those farmers who have stayed in the area for more than twenty years were used in the selection criteria.

Agriculture extension enumerators that were conversant with the study areas were hired to conduct the household interviews during the field research. Before the interviews were carried out, enumerators received field training on the survey instruments and ethical considerations of this research. Interviews were conducted using structured questionnaires. To minimize bias, questions were interactive and farmers were allowed to indicate other answers in case the stated options did not meet their responses. This technique was useful in exploring the responses of the farmers to gather more and deeper information on the subject and the interviewing technique ensured a 100% return rate of the questionnaire.

In addition to the interview survey, three focus groups meetings were held in each district whereby each group was composed of 15 farmers. The focus group discussions were carried out with the anticipation of a wider range of responses from group responses thereby allowing participants to build on each other's ideas and comments. Knowledge, in this context, refers to what farmers know about the problem of vegetable pests and their response to a changing climate while management practices refer to the actual actions that farmers take to control insect pests. Information was collected on climate induced risks affecting vegetable production, the corresponding vegetables affected, the status of natural enemies, an estimate of crop losses as a result of insect pest attack and the various practices to reduce insect pest hazard in a changing climate. On natural enemies, photographs were also used for the correct identification of natural enemies that prey upon some common insects in the country.

A one-way analysis of variance ANOVA at $P<0.05$ was conducted to assess any differences in farmers responses between the agro-ecological zones using SPSS version 16. At $P<0.05$, a mean comparison was used to determine the agro ecological regions that exhibited significant differences. Descriptive statistics such as means and problem ranking matrices were also used in the study to generate summaries and tables.

4.3 Results

4.3.1 Major climate induced challenges to vegetable production

The survey results revealed that across all the agro ecological regions surveyed, there was no significant difference ($P>0.05$) on the challenges that are encountered by farmers in vegetable production. The majority (44.8%) of the respondents across the agro ecological regions cited droughts and the inadequate irrigation water as the major challenge to vegetable production. Insect pests, plant diseases and weeds were cited by 24%, 24% and 11.2% of the respondents respectively (Table 4.1).

Table 4.1: Major climate induced challenges to vegetable production (% responses; N=250).

Variable	NR1	NR2	NR3	NR4	NR5	mean	P-value
Challenges							
Droughts	38	40	34	48	44	44.8	NS
Vegetable insect pests	22	26	22	26	24	24	NS
Plant diseases	34	22	28	14	22	24	NS
Weeds	6	12	16	12	10	11.2	NS
Total	100	100	100	100	100	100	

NB: There are no significant differences at $p>0.05$, NS-not statistically significant

4.3.2 Extent of crop losses from insect pests and disease attack

Across the agro ecological regions, 53% reported high vegetable losses, 27% indicated that the losses from insects and diseases were moderate and 20% stated that the losses due to insects and diseases were low. However there were highly significant differences ($p<0.05$) on the extent of crop losses between the agro ecological regions. The extent of vegetable losses in NR 1, 2 and 3 were significantly higher compared to the extent of vegetable losses encountered in NR 4 and N5 (Table 4.2).

Table 4.2: Extent of crop losses from insect pests and disease attack (% responses; N=250).

Variable	NR1	NR2	NR3	NR4	NR5	mean	P-value
High	52	72	76	34	32	53	0.00*
Moderate	38	10	10	42	34	27	0.00*
Low	10	18	14	24	34	20	0.00*
Total	100	100	100	100	100	100	

NB: There are significant differences at $p<0.05$, * significant differences at $p<0.01$

The participants of the focus group discussions concurred that the increase in vegetable attack due to insect pests as well as insect pest outbreaks in the past decade is mainly attributed to long dry spells and high temperatures during the production seasons. The views of the farmers in terms of drought conditions were also in agreement with recorded meteorological data analysis which indicates that the first decade of the 21st century, had the highest frequencies of droughts (8 droughts) compared to the previous decades in the late 20th century (Table 4.3).

Table 4.3: Frequency of drought events in Zimbabwe from 1950-2010.

Weather events	Extreme droughts	Severe droughts	Moderate droughts
Drought years	1982, 1983	1968, 1973, 1982, 2004	1951, 1960, 1964, 1965 1970, 1984, 1987, 1991 1995, 2002, 2003, 2005 2007, 2008, 2009, 2010
Total	2	4	16

Source: Meteorological Services Department (2013)

4.3.3 Farmer ranking of major vegetable insect pests

Using the problem ranking matrix, the top three insect pests that were key in vegetable production across all the agro ecological regions were aphids which were cited by 100% of the respondents, cutworms cited by 98% and whiteflies which was cited by 86%. However beetles were the least cited insect pests with a fewer respondents (34%) compared to the other insect pests (Table 4.4).

Table 4.4: Farmer ranking of major vegetable insect pests on a scale from 1(most serious) to 10 (least serious) (% responses; N=250).

Insect	NR1	NR2	NR3	NR4	NR5	mean	Ranking
Aphids	100	100	100	100	100	100	1
Cutworms	100	100	100	86	84	98	2
Whiteflies	92	96	84	82	76	86	3
Diamond Back Moth	82	100	100	60	76	84	4
Leaf miners	84	92	98	40	44	72	5
Cabbage Loopers	66	80	60	40	24	54	6
Thrips	74	80	60	26	20	52	7
Fruit flies	64	42	60	26	18	42	8
Beetles	48	38	26	42	14	34	9
Army worm	33	40	38	23	20	31	10

NB: Percentages exceed 100% due to multiple responses
Source: Survey data (2015)

In the focus group discussions, aphids were also cited by the majority of the farmers who highlighted that the insect pest feed on a wide range of field crops, vegetables, ranging from the brassicas (rape, cabbages, mustard), solanaceous (tomatoes, potatoes), cucurbits (squashes, pumpkin) and other vegetable families. In addition, the farmers indicated that the aphids can also be found on some weed species. Of late they have indicated that they have found some aphid species on maize. The diamond back moth was cited as a common insect pest amongst the leafy vegetables such as rape, kale, cabbages and cauliflower. Farmers cited that most of the damage caused by the insect pests resulted in the destruction of the vegetable foliage, reduction in the quality of leafy vegetables, stunted growth and sometimes death of the plants. However the majority of the farmers were not aware of the ability of the insect pests to transmit plant diseases although from our field observations, there were disease symptoms which were shown by the mosaic patterns on vegetables like the tomatoes that were infested with aphids.

4.3.4 Farmer choice of synthetic insecticides used in insect pest management

Management of increasing abundance of insect pests included the use of various chemical insecticides which included the synthetic carbamates (carbaryl and aldicarb) and organophosphates (acetamiprid, malathion, diazinon, tamaron, monocrotophos and chlopyriphos). Organochlorines that were used by the farmers include dicofol as well as the pyrethroids such as fenvalerate. However some farmers use insecticides that are intended for use on non-food crops such as tobacco and cotton (monocrotophos, tamaron) citing that the green labelled chemicals that are intended for use on vegetables such as dimethoate (locally known as rogor) are no longer effective and have resorted to use of red labelled chemicals which are highly toxic. The chemicals that were cited as being effective by the farmers are mainly the chemicals in the high to extreme toxicity group (Table 4.5).

Table 4.5: Farmers choice of the synthetic pesticides used to control vegetable pests in a changing climate and the period of high insect pest incidence.

Insect pest	Period of high pest Incidence	Insecticides	Colour of label
Aphids	All year round	Dimethoate	Green
		Malathion	Green
		Diazinon	Green
		Fenvalerate*	Red
		Chlopyriphos*	Red
		Lambda*	Red
		Tamaron*	Red
		Dithane M45	Green
		Monocrotophos*	Red
Whiteflies	Hot season	Fenvelerate	Red
		Malathion	Green
		Diazinon	Green
RSM	Hot season	Dicofol	Amber
Leaf miners	Hot season	Monocrotophos*	Red
		Carbaryl	Amber
DBM	All year round	Diazinon*	Green
		Carbaryl*	Amber
		Malathion	Green
Thrips	Hot season	Malathion	Green
Cutworms	All year round	Chlopyriphos	Red
		Lambda	Red
Leaf hopper	Hot season	Carbaryl	Amber
Grasshopper	Hot season	Carbaryl	Amber
CL	Warm weather	Carbaryl	Amber

NB: Source (Focus group discussions, 2015). CL-Cabbage Looper, DBM-Diamond Back Moth. *Indicates an insecticide that is not registered for use on a particular pest in vegetables

4.3.5 The frequency of spraying effectiveness of synthetic insecticides

Across the five agro-ecological regions, all the respondents (100%) interviewed indicated that they use chemical insecticides to manage insect pests at some point during the production cycle of the vegetables. There was no significant difference in the frequency of chemical insecticide spraying across the 5 NRs ($P>0.05$). Forty four percent of the respondents stated that they spray vegetables at an average frequency of once per month, while 29% sprayed twice per month and 27% spray vegetables more than two times per month, indicating high rates of insecticide use (Table 4.6).

There was a significant difference on the perceived effectiveness of the chemical insecticides within the 5 agro ecological regions of the country. A higher number of respondents in NR1, NR2 and NR3 stated that the chemical insecticides were effective. The responses of farmers in NR 1 and NR2 were significantly different from those of NR4 and NR5 at $p<0.05$ while the responses of farmers in NR3 were significantly different from those of NR5. The farmers in NR4 and NR5 felt that the chemical insecticides were ineffective. Across the natural regions, the majority (60%) of the farmers highlighted that the chemical insecticides were effective while 34% felt that some insecticides were ineffective and 6% had mixed feelings on the effectiveness of the chemical insecticides (Table 4.6).

Table 4.6: Farmers perceptions of the frequency of spraying effectiveness of synthetic insecticides and their effectiveness (% responses; N=250).

Variable	NR1	NR2	NR3	NR4	NR5	Mean	P-value
Frequency of spraying							
Usage of synthetic chemicals	100	100	100	100	100	100	NS
Once per month	44	44	38	42	52	44	NS
Twice per month	28	30	32	30	24	29	NS
More than twice per month	28	26	30	28	24	27	NS
Effectiveness of insecticides							
They are very effective	76	74	60	50	40	60	0.001*
They are not effective	22	20	34	42	50	34	0.001*
They are somewhat effective	2	6	6	8	10	6	0.001*
Total	100	100	100	100	100	100	

NB: There is a significant difference at $P<0.05$, *significant at $P<0.01$
Source (Survey data, 2015).

In the focus group discussions, the majority of the discussants did not know the role that is played by natural enemies in the control of insect pests. However, the natural enemy that some farmers knew was the lady bird beetle and it was indicated that its population had declined. However from our observations, the fields that were frequently sprayed (sprayed for at least twice per month) with chemical insecticides had no signs of any natural enemy compared to fields that were sprayed less frequently (once per month) which hosted some ladybird beetles.

4.3.6 Insect pest management strategies used by the farmers

There were no significant differences (P>0.05) on the major insect pest management strategies that was implemented by the farmers across the 5NRs. Across all the agro ecological regions the majority (28.8%) of the farmers intercrop vegetables with other plants (e.g. kale intercropped with garlic, *Allium sativum* and onion, *Allium cepa*. This was followed by the use of chemical mixtures which was practised by 25.2% of the respondents. Trap cropping was practised by 20.4% while 5.6% removed plants that were severely infested with insect pests from the fields and 20% rotated vegetables for insect pest control (Table 4.7). In the focus group discussions, the farmers highlighted that they have adopted the cultural measures from the use of plant extracts such as using the apple of Peru (*Nicandra physalodes*), chilli (*Capsicum annum*) extracts, garlic extracts, increasing diversity of vegetable crops within the field, reduction in the size of land areas that are under vegetable production, location of vegetable gardens near homesteads where they can constantly monitor insect pests and take appropriate control measures. Regular weeding in and around vegetable gardens was also highlighted by the farmers as an important measure used to control insect pests as the weeds were found to harbour some insect pests which would spread easily to the adjacent vegetable crops if the weeds are not controlled. Farmers have also highlighted the production of a vegetable variety of kale which was reported to be less affected by a number of insect pests including the aphids.

There was no significant difference between the farmers' responses in the five agro ecological regions on the source of insect pest management information. The majority (57.2%) indicated that they obtain insect pest management information from the agriculture extension officers while 31.2% obtain the information from fellow farmers and the lowest (11.6%) number of respondents obtain information from various Non-Governmental Organisations (NGOs). However, it was noted that the extension officers in the various wards are not specialised in crop protection and crop protection services are obtained at district and provincial offices of the Ministry of Agriculture. Results from the FGDs indicate that farmers also get information on insect pest management from agronomists of the various agro chemical companies such as agricura and ZFC during field days.

Table 4.7: Major adaptive strategies for insect pest management in a changing climate and the source of insect pest management information (% responses; N=250).

Variable	NR1	NR2	NR3	NR4	NR5	mean	P-value
Insect pest management strategy							
Mixing insecticides	28	28	24	24	22	25.2	NS
Use of trap crops	22	22	20	22	16	20.4	NS
Removal of affected crops	6	6	8	2	6	5.6	NS
Intercropping	28	28	26	30	32	28.8	NS
Crop rotation	16	16	22	22	24	20	NS
Total	100	100	100	100	100	100	
Source of pest management information							
AREX	68	62	56	48	52	57.2	NS
NGOs	8	2	2	24	22	11.6	NS
Fellow farmers	24	36	42	28	26	31.2	NS
Total	100	100	100	100	100	100	

NB: There is no significant differences at $p>0.05$, NS-Not significant

Source (Survey data, 2015).

4.4 Discussion

The majority of the farmers across the natural regions were aware of climate induced challenges to vegetable production similar to studies that were carried out in Uganda (Okonya et al., 2013). In this study, climatic factors affected vegetable production leading to low yield because vegetables crops are very sensitive to environmental extremes, and therefore high temperatures and limited soil moisture exacerbated by climate change directly though yield losses and indirectly through increases in insect pest population, reduce productivity in the tropical regions (Singh & Singh, 2013; Singh & Bainsia, 2015).

Insects and diseases have been cited as some of the major biological challenges to vegetable production under a changing climate. These findings correspond with the majority of the studies that were conducted in several African countries which showed that insect pests and crop diseases are some of the greatest challenges to vegetable production in an environment of a changing climate (Emana et al., 2015; Midega et al., 2013). In other studies, Munthali & Tshegofatso (2013) and Norman et al. (2014) in Botswana and Sierra Leone respectively showed that the majority of the farmers surveyed associated vegetable yield loss to insect pests attack under warming climate conditions. In a related research that was carried out in Tamil Nadu in India, farmers perceived insect pests as the most critical bioclimatic challenge resulting in 65-70% of vegetable loss as a result of the destructive activities of insects such as fruit borers, Leucinodes *orbonalis*, Guenée 1854 (Lepidoptera: Crambidae) whiteflies and thrips, *Thrips tabaci*, Lindeman 1889 (Thysanoptera: Thripidae) (Schreinemachers et al., 2015). This suggests that much of the damage on vegetables and related losses were attributed to insect pests attack whose destructive activities are aggravated by a warming climate.

The farmers reported an increase in insect pest abundance with the top three vegetable insect pests being the aphids, cutworms and the whiteflies. Aphids being more abundant under warm conditions, are also found on the growing points of vegetables therefore making them more visible to the farmer. Cutworm was ranked as another important insect pest of vegetables. The arrival of cutworms early in the life cycle of vegetables where they cut down the seedlings make them noticeable by the farmers (Okonya & Kroschel, 2015).

The use of chemical insecticides by all the respondents as well as their perceived effectiveness across the agro-ecological regions was in line with studies that were carried out in Thailand, Vietnam, India and Pakistan which showed that all the smallholder farmers in these Asian countries relied heavily on synthetic insecticides to control insects' pests (Khan & Damalas, 2015; Schreinemachers et al., 2015). In Pakistan, Punjab district, all the farmers surveyed reported using insecticides extensively as the only effective method of controlling insect pests (Khan & Damalas, 2015; Khan et al., 2015). The perceived reduced efficacy of some insecticides such as dimethoate in the hotter agro ecological regions could also have been due to some extreme weather events which degrades most organophosphates at elevated temperatures thereby rendering many of the chemical insecticide products to be less effective

(Musser & Shelton, 2005). The increase in insect pests abundance could also have led to increased use of chemical insecticides among the farmers (FAO, 2006) which in turn led to insect resistance due to continuous use of the insecticides (Fand et al., 2012; Cothran et al., 2013). This therefore calls for further increases in the rates of insecticide application and the use of more hazardous chemical insecticides. The use of the hazardous chemical insecticides were in line with the study of Khan et al. (2015) in Pakistan who noticed that 55% of the smallholder farmers used moderately hazardous while 23% used highly hazardous chemical insecticides because of their perceived effectiveness compared to the mild insecticides.

Farmers cited reduced effectiveness of natural enemies while others were not sure of the status and role that is played by natural enemies in insect pest control. This could have been as a result of poor knowledge of natural enemies among the smallholder farmers, as was also observed in other African countries such as Benin (Loko et al., 2013) and Uganda (Okonya & Kroschel, 2016). In addition, excessive use of synthetic insecticides could have also eliminated both target and non-target species thereby increasing the susceptibility of natural enemies to insecticides and a corresponding reduction in their populations (Chidawanyika et al., 2012; Selvaraj & Pandiara, 2013). In addition to excessive use of chemical insecticide, the small and delicate nature of most of the natural enemies also makes them susceptible to weather extremes (extreme temperature, strong winds and heavy rainfall) which are characteristic of a changing climate thereby resulting in a decline in their populations (Fand et al., 2012; Gerard et al., 2012). In an experimental study that was carried out in Southern California, a 3°C increase in average summer temperatures resulted in a reduction in offspring production by about 90% for an important beneficial wasp, *Cotesia marginiventris* Cresson (Hymenoptera: Braconidae) (Trumble & Butler, 2009). This therefore means that with a warming climate, there is most likely a reduction in the abundance of natural enemies.

The use of chemical mixtures in this study was similar to the practice of the majority of smallholder farmers in Asian countries who mix various synthetic insecticides into single sprays in order to effectively control crop pests (Khan & Damalas, 2015; Okonya & Kroschel, 2015; Schreinemachers et al., 2015). Insecticide mixtures have a synergistic effect in insect pest control thereby enhancing the effectiveness of insect pest control under warming conditions (Abd El Mageed & Shalaby, 2011).

Cultural insect pest management practices such as intercropping, removal of heavily infested plants and switching to insect and resistant cultivars have also been manipulated by smallholder farmers to manage insect pests. Specialist insects such as the diamond back moth (*Plutella xylostella*), which only attacks cruciferous crops, are an example of insect pest with a narrow host range thus can be managed by intercropping with a crop that belongs to a different family (Smith & Liburd, 2015). Intercropping a susceptible and a non-susceptible crop controls insect pests by interfering with the ability of an insect to detect host plants by the production of a volatile chemical compound by a component crop that confuse the insect (Smith & Liburd, 2015).

Removal of heavily affected plants and the use of disease resistant plant varieties was practiced by sweet potato farmers in Tanzania where 72% of the farmers in the Mara region removed affected plant from the field while (55%) stopped growing a variety in their field or got a resistant plant material (Adam et al., 2015). This management strategy reduces the chances of migration of insect pests to adjacent healthy crops or fields (Okonya & Kroschel, 2016).

Trap cropping in results in fewer pests on the main crop than if the trap crop were not present especially in specialist insects such as the diamond back moths (Zhou et al., 2011). In Florida, a plant of the Brassica family, collard greens (*Brassica oleracea var. acephala L.*) has been used as a trap crop to suppress infestations of diamond back moth larvae in cabbages, resulting in lower population of insect pests in the collard greens (Mitchell et al., 2000). In an experiment where tobacco was produced, *Colocasia esculenta* hosted large numbers of the adults of second generation *S. litura* and provided adult females with an optimal oviposition site, hence the number of egg masses on tobacco was lower in trap cropping than in treatments where the tobacco pest was chemically controlled (Zhou et al., 2011).

Farmer support services such as agricultural extension services increases farmer knowledge on the risks associated with climate change as well as the management options (ATPS, 2013). Other sources of insect pest management information such as the NGOs had fewer respondents but were important in the dissemination of pest management information. This was in line with a study that was carried out in Tanzania which showed that apart from farmer extension services as the main source of information, farmers can also acquire information on various production practices through other means such as farming experience and various informal networks (Adam et al., 2015). In a related study that was carried out in Italy, it was shown that farmers' field days were an effective way of communicating risks and adaptation options to a changing climate (Menapace et al., 2015).

4.5 Conclusion and recommendations

Increasing temperatures, increased abundance of insect pests, plant diseases and weeds have been identified by the farmers as the major challenges to vegetable production under a with increasing incidence of major insect pests such as the aphids, cutworms and whiteflies across all the natural regions. Chemical insect pest management through application of increased insecticide rates, increased frequency of application and mixing chemical insecticides have been found to be the major strategies that the farmers were using for the management of insect pests resulting in overuse of chemical insecticides. Cultural pest management strategies such as intercropping, crop rotation, removal of affected crops and use of trap crops have also been used by farmers to control insect pests. This study revealed that smallholder farmers have little knowledge of natural enemies of insect pests and the role that they play in insect pest management, therefore there is a need to train smallholder farmers or improve their understanding on the identification as well as the role that can be played by natural enemies in insect pest management. Farmer training on adoption of more environmentally friendly strategies such as Integrated Insect Pest Management (IIPM) to reduce over reliance on chemical insecticides and therefore adapt to increasing insect pest challenges under a changing climate is also of importance. There is also need for improvement in the extension services by the government where specialists in crop protection need to be in close proximity to the farmers, than being stationed at the district or provincial offices. Forewarning models for predicting insect arrival, presence, absence or abundance based on earlier climate profiles will be of importance in order to provide a more precise spatial distribution of insect pests in the various agro ecological regions of Zimbabwe which assists in estimating the potential vulnerability of the farmers to insect pest risk.

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CHAPTER 5

MAPPING THE CURRENT DISTRIBUTION OF THE APHID, *MYZUS PERSICAE* IN AGRICULTURAL PRODUCTION REGIONS IN ZIMBABWE.

Abstract

The increase in global trade and changes in climate have resulted in the spread and establishment of aphids in different parts of the world including Zimbabwe. The objective of the research study was to map out the distribution of aphids, *Myzus persicae* Sulzer (Hemiptera: Aphididae) in all the 5 agro ecological regions of Zimbabwe that could guide assessment of agricultural risk to the insect pest as well as highlighting the potential for future research. The areas that were surveyed and represented the five agro ecological regions from natural region 1 to 5 respectively are Chipinge, Goromonzi, Mutoko, Masvingo and Chiredzi districts. An insect distribution modelling approach, the Random Forest (RF) algorithm, was applied using bioclimatic data. The results from the RF model indicates that precipitation related variables were of more significance in determining the potential current distribution of *M. persicae* compared to the temperature related variables with an overall accuracy of 70% and a kappa value of 0.64 implying that the model was reliable. Chipinge, Goromonzi and Mutoko had been shown to have the largest area that is suitable for *M. persicae* under the bioclimatic datasets compared to Masvingo and Chiredzi under current climatic conditions. The study concludes that vegetable farmers in Chipinge, Goromonzi and Mutoko are currently vulnerable to the effects of *M. persicae* attack on vegetable crops as well as the corresponding plant diseases. There is need for insect pest management measures to be put in place mainly targeting Chipinge, Goromonzi and Mutoko districts to reduce farmer vulnerability to yield loss as a result of the presence of *M. persicae* and the corresponding pathogens that are transmitted by the insect pest. Projection of future risks of the various agro ecological regions to virus vectors is of importance to enable timely planning of management measures in the areas where insects are anticipated in the future.

Keywords: current distribution, *Myzus persicae,* Random Forest

5.1 Introduction

Aphids, *M. persicae* originated from Asia (Blackman & Eastop, 2000). The increase in global trade and current changes in climate have resulted in the introduction and establishment of the aphid species into the different regions of the world where they are currently found (Akyıldırım et al., 2013; Beddow et al., 2010). Aphids are considered an important insect pest species group due to their minute size, high reductive potential (Munthali & Tshegofatso, 2014), short life cycles, cyclical parthenogenetic reproduction, host preferences, and a close relationship with the host plants (Mondor & Addicott, 2007). The life cycle of *M. persicae* may have a holocyclic (sexual) or anholocyclic (asexual or incomplete life cycle). Parthenogenetic (asexual types) females hatch in spring and they disperse to secondary host plants where they produce many parthenogenetic generations (Blackman and Eastop, 2000). When aphids are continuously reproduced in a parthenogenetic manner they can achieve up to 18 generations a year (Harrington, 2007).

Due to the ectothermic nature of the majority of insects including the aphids, are very likely to respond quickly to increased temperatures (Robinet & Roques, 2010), and rising temperatures have the potential to affect most life history parameters of terrestrial insects, altering their ecological roles, as well as intra- and inter-specific interactions (Chidawanyika et al., 2012). Yamamura and Kiritani (1998) suggested that aphids are amongst the insects that are best adapted to take advantage of a warming climate, and could go through an extra five generations a year following a warming of 2°C. It is also suggested that besides increases in CO_2 concentration as a result of climate change, differences in soil nitrogen content and population density also play a part for aphid abundance (Newman et al., 2003).

Aphids are commonly known for their ability to rapidly colonize high value crops and other economically important plant species such as the solanaceous crops, brassicas as well as ornamentals (Chemura et al., 2013; Marava, 2012). The large numbers of *M. persicae* weaken juvenile plants (Mhazo et al., 2011; Saljoqi, 2009), cause leaf stunting, yellowing and curling on mature plants (Opfer & McGroth, 2013). During feeding on older plants, they simultaneously ingest sap contents, weakening the plants (Mhazo et al., 2011) while at the same time injecting saliva, which can contain viruses if *M. persicae* has previously fed on an infected plant (DEEDI, 2009). This results in gall formations on stems and leaves which are unsightly to the crops. In addition, they also excrete huge quantities of sticky honeydew, which promotes the growth of sooty mould which attract ants, thereby reducing photosynthesis (Masuka et al., 2010). The high reproductive rates and mobility of aphids contribute to their efficiency to act as virus vectors (Warren et al., 2005; Webster, 2012). All potyviruses (the largest group of plant viruses) cause serious damage to the field as the population size of *M. persicae* increase (Obopile et al., 2008). The viral infections on the plants alter the biochemistry of the plants to make them smell and taste different to the insect pest vector which results in the insects spreading the virus further (Ladanyi & Horvath, 2010) thereby leading to food insecurity as a result of yield loss.

In Zimbabwe, the response of *M. persicae* to climate was monitored over a long period of time. Monitoring studies indicated a change in the morphs of *M. persicae* to the emergence of new morphs that are more adaptable to a warming climate. The new *M. persicae* morphs have been reported to be insecticide resistant and also have a more prolific reproductive cycle compared to the earlier morphs (Masukwedza et al., 2013). The emergence of the new morphs are therefore responsible for the transmission of several types of viral diseases in tobacco in Zimbabwe (Dimbi, 2014)

Determining the current distribution of insect species have received little attention in most countries (Gormley et al., 2011). However, insect pest distribution models have been developed on a global scale (Kumar et al., 2015; Tannong et al., 2015). Some models have been developed for several insects in Asia (Solhjouy-Fard et al., 2013), North America (Kumar et al., 2014) and Europe (Barredo et al., 2015). Very few modelling approaches have been carried out in Africa (DeMeyer et al., 2010) and more specifically Zimbabwe. Research that was conducted in East Africa focused on the distribution of the coffee insect pests such as, white stem borers (Jaramillo et al., 2011), coffee leaf miner and the antestia bug (Brown, 2008). In South Africa, the majority of the modelling studies concentrated on forest insects and diseases (Adam et al., 2013; Ismail et al., 2010) while in Zimbabwe a modelling study that was conducted, focused on the coffee white stem borer (Kutywayo et al., 2013). A greater proportion of the studies that were carried out with respect to climate change modelling in Zimbabwe mainly dealt with cereal crop growth and yield modelling (Masanganise et al., 2012; Matarira et al., 2011). Considering the significance of insect pests to yield losses, assessing the spatial distribution of insect pest is of importance (Biber-Freudenberger, 2016). The development of a distribution model of insect pests is of importance since insect pests are ectothermic and therefore their biology is governed by environmental conditions (Seidl, 2011).

M. persicae are herbivorous insect species that has received little attention in distribution studies (Mondor & Addicott, 2007). Determining the current spatial occurrence of the established aphid is of significance in enabling a better understanding of the distribution of insect pest (Whatt et al., 2011). It is also a significant step in evaluating eradication efforts by the farmers (Phillips et al., 2006). In addition, it also provides a better understanding of the basic factors that affect pathogen dispersal (Liu et al., 2006). The objective of this study was therefore to map the current distribution of *M. persicae* in the various agro ecological regions of Zimbabwe thereby estimating the potential vulnerability of the farmers to the risk of *M. persicae* and the corresponding plant diseases.

5.2 Materials and Methods

5.2.1 The study area

The study area was described in section 3.2.1.

5.2.2 Field data collection

Field surveys were conducted in the 5 agro ecological zones in both the winter and summer seasons for 2015 and 2016 to monitor and capture information related to the presence and level of infestation of *M. persicae*. These were carried out in each agro-ecological zone and where 10 tomato producing farms were randomly surveyed. Ten farmers that were perceived by the extension farmers to be active in production of horticultural crops including the tomatoes in the respective regions were randomly chosen from a list of active farmers. At each of the sampling farms, sample plots (30 m x 30 m) were recorded using a Global Positioning System (GPS) (Garmin e Trex Vista). *M. persicae* abundance was measured from 10 randomly selected plants using a 0-4 scale of *M. persicae* intensity, where 0 referred to no *M. persicae* infestation, 1 referred to low infestation where 1 or 2 *M. persicae* were found on plant leaves, 2 referred to mild infestation where large numbers of *M. persicae* were found but on a few leaves 3 referred to high infestation where *M. persicae* were found on numerous plant leaves and 4 referred to very high infestation where *M. persicae* families were numerous on most plant leaves resulting in curling and twisting of the leaves. In addition, the level of infestation of *M. persicae* was determined by checking the signs of *M. persicae* damage which included wrinkled leaves, the presence of sooty moulds accompanied by ants, yellowing of the leaves as well as mosaic symptoms on the vegetable leaves. The points from which field surveys were conducted are shown in Fig 5.1.

5.2.3 Input Climatic Variables

Nineteen bioclimatic variables (BIOCLIM) (Nix, 1986) representing current climate conditions across Zimbabwe were utilized and sourced from the WorldClim database (Hijmans et al., 2005). The bioclimatic variables are obtained from monthly temperature and rainfall values that are drawn from the years 1960–1990 (Table 5.1). Each bioclimatic variable was used in conjunction with the observed field data as potential predictor of *M. persicae* distribution.

Table 5.1: Bioclimatic layers used in the random forests model

BIO1-Annual mean temperature
BIO2-Mean diurnal range (mean of monthly temperature (max-min temperature)
BIO3-Isothermality BIO2/BIO7×100
BIO4-Temperature seasonality (standard deviation ×100)
BIO5-Max temperature of wettest month
BIO6-Min temperature of coldest month
BIO7-Temperature annual range (BIO5-BIO6)
BIO8-Mean temperature of wettest quarter
BIO9-Mean temperature of driest quarter
BIO10-Mean temperature of wettest quarter
BIO11-Mean temperature of warmest quarter
BIO12-Annual precipitation
BIO13-Precipitation of wettest month
BIO14-Precipitation of driest month
BIO15-Precipitation seasonality (coefficient of variation)
BIO16-Precipitation of wettest quarter
BIO17-Precipitation of driest quarter
BIO18-Precipitation of warmest quarter
BIO19-Precipitation of coldest quarter

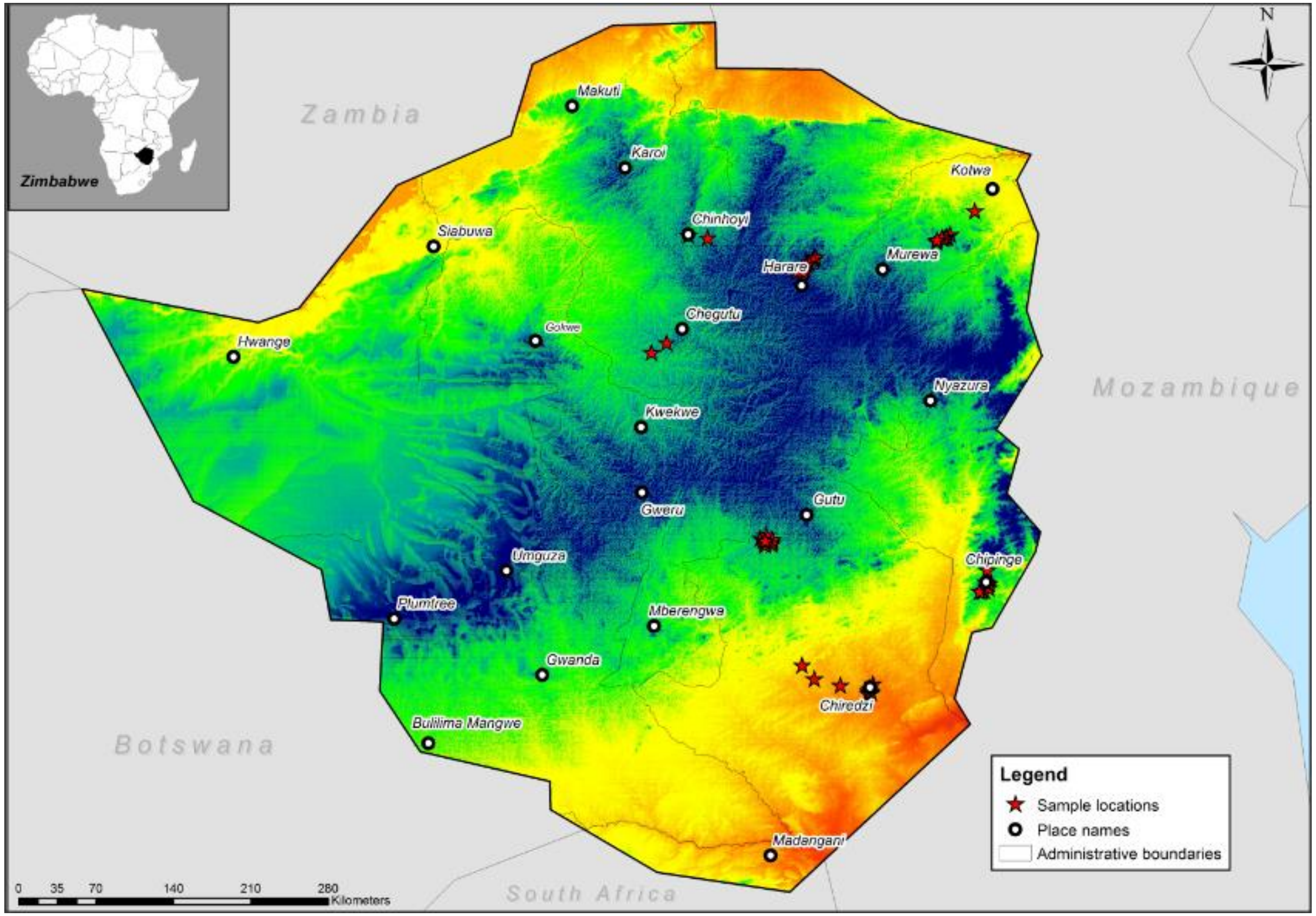

Fig 5.1: A national map showing the sample locations.
It indicates the data points from which samples were taken

5.2.4 The Random Forest modelling approach

Random forest is a competent classification model that is designed to produce accurate results that do not over fit the data (Breiman, 2001). It was designed to extract the maximum amount of information from field observations and experimental data when there are insufficient data to build a detailed simulation model of the species. In a Random Forest, the features are randomly selected in each decision split. The correlation between trees is reduced by randomly selecting the features which improves the prediction power and results in higher efficiency (Brieman, 2001; Lin, 2011).

Random Forest builds numerous binary classification trees (*ntree*) using several bootstrap samples with replacement which are drawn from the initial observations in the first stage. The *ntree* contributes a unit vote and the correct classification and the actual classification is determined by the majority vote from all the trees in the forest. The samples that are not included in the bootstrap sample are known as out of the bag (OOB) samples. These are used to estimate the misclassification error as well as the importance of the variable under consideration. In the second stage, at each node, a given number of input variables (*mtry*) are randomly chosen from a random subset of the features and the best split is calculated using this subset of features. As a way of ensuring low similarity and hence low bias, all the trees of the forest are not pruned (Breiman, 2001; Lin et al., 2011). The *mtry* and the *ntree* parameters are recommended to be optimised to improve the classification accuracy (Adam et al., 2011; Ismail et al., 2010; Genuer et al., 2010).

5.2.5 Random forest model validation

Accuracy assessment entails the comparison of a classification with ground truth data to evaluate how well the classification represents the situation on the ground. It was calculated using the confusion error matrix (Congalton & Green, 1999). The dataset collected from the field 100% (n = 50 farms) were split into training data, (60%; n = 30) and test data (40%; n = 20). The whole process was repeated a 100 times to take into consideration the variation that could arise as a result of training and validation samples (Peerbhay et al., 2014; Fassnacht et al., 2014). Class accuracy was obtained by examining the user's and the producer's accuracies. The producers accuracy (omission error) refers to how well a certain area can be classified while the users accuracy (commission error) is a measure of reliability, probability a pixel class on the map represents the category on the ground. The producer's accuracy was calculated by dividing the number of correctly classified species in each class by the size of the training sample used for that class also known as the column total. On the other hand, the user's accuracy was calculated by dividing the number of correctly classified species by the number of species that were classified in the particular class also known as the row total in the confusion matrix. The overall accuracy is therefore obtained by dividing the total number of correct pixels by the total number of pixels in the error matrix. A discrete multivariate technique known as Kappa analysis was also conducted to determine the significant difference between one error matrix and another. It is a measure of agreement between classification map and reference data. Kappa analysis uses the *k* (KHAT) statistic, where coefficients that are closer to or equal to one assume perfect agreement. (Congalton & Green, 1999). In this study, field data scores were split into training and test datasets, whereby a portion was used to train the model based on the observations in field. The test dataset was then used for validation of the model once complete it was used to assess the accuracy of the overall model performance.

5.3 Results

5.3.1 Mapping the distribution of *M. persicae* using bioclimatic variables

Utilising the random forest approach, the final classification results using the test dataset are shown in Table 5.2. An overall classification accuracy of 85% was produced for determining the presence and absence of the *M. persicae* during summer (*ntree* = 3500 and *mtry* = 2) with a kappa value of 0.63 and producer and user accuracies between 67 and 93. For winter, results indicate a reduced classification accuracy of 80% with a kappa value of 0.50 and user and producer accuracies ranging between 58 and 89.

Table 5.2: Accuracies from the RF model based on the presence/absence data

	Summer		**Winter**	
	Presence	Absence	Presence	Absence
Producers accuracy	80	67	70	58
Users accuracy	67	93	83	89
Kappa	0.63		0.5	
Overall Accuracy	85%		80%	

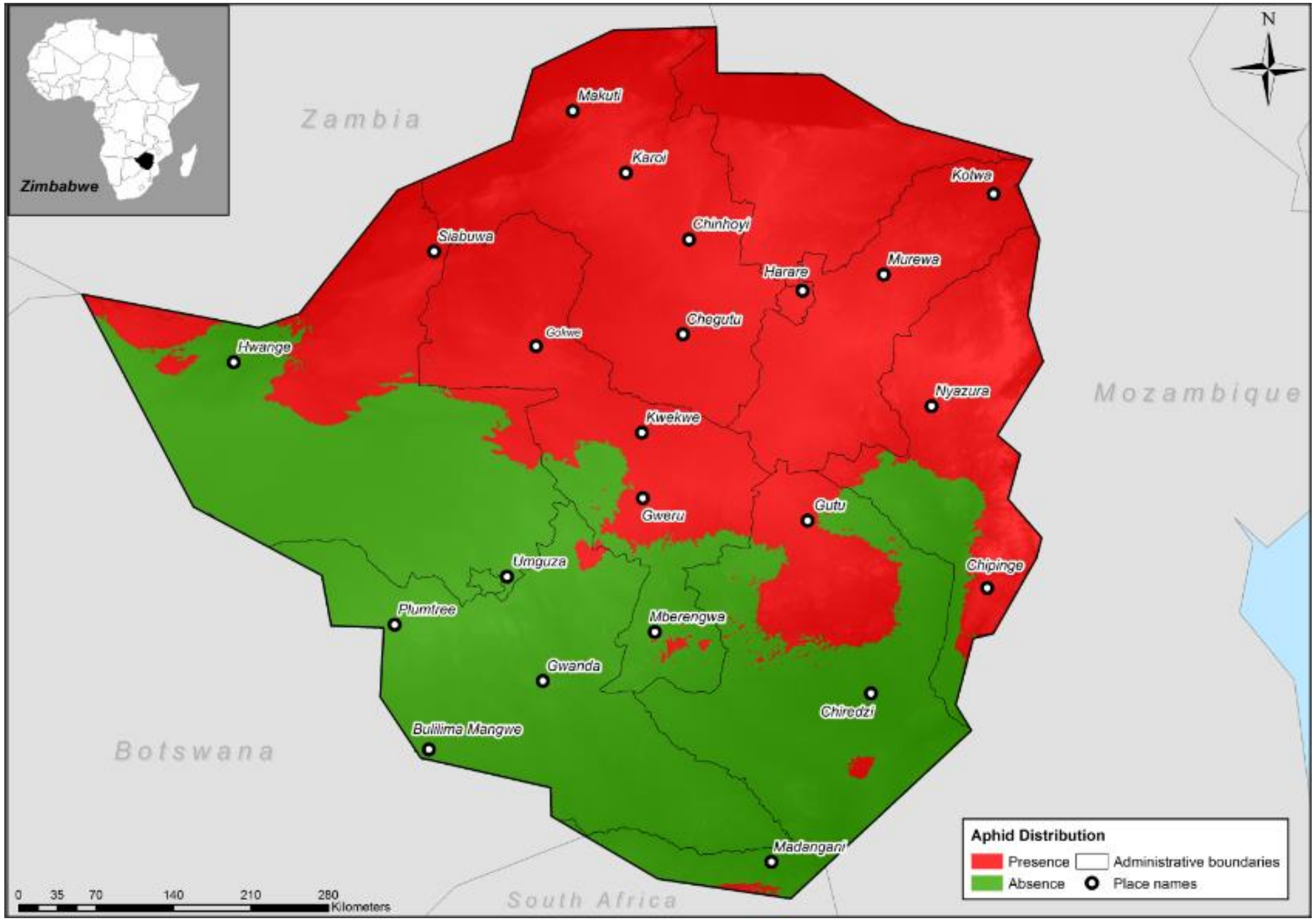

Fig 5.2: A national map showing the spatial distribution of *M. persicae* using the RF model based on presence/absence data. The map indicates that *M. persicae* is most likely to be abundant in the northern part of the country compared to the southern part of Zimbabwe.

5.3.2 Mapping *M. persicae* infestation levels

While the presence and absence analysis provided baseline information regarding the spatial distribution of the *M. persicae*, it does not provide further detailed information on the level of infestation (Fig 5.2). Therefore, we utilized the information collected in field, from each NR and from each farm based on the infestation levels of the *M. persicae*. Using the RF approach the final classification accuracies are indicated (Table 5.3). The results from the RF indicates that an overall classification accuracy of 70% was obtained for determining the various levels of *M. persicae* infestation during the summer (*ntree* = 4500 and *mtry* = 4) with a kappa value of 0.64 and producer and user accuracies ranging between 50 and 100%. For the winter season, the results indicate a lower classification accuracy of 60% with a kappa value of 0.52 with producer and user accuracies ranging between 40 and 75% (Table 5.3).

Table 5.3: Final classification accuracies based on the level of infestation using the RF model

	Summer		Winter	
	Users accuracy	Producers accuracy	Users accuracy	Producers Accuracy
None	60	75	66	70
Low	100	75	60	70
Moderate	67	50	65	60
High	60	75	40	50
Very high	75	75	50	50
Kappa	0.64		0.52	
OA	75%		60%	

Figure 5.4 shows the spatial distribution of the *M. persicae*. Noticeable is the high level of *M. persicae* infestation in the districts in NR 1 (Chipinge and Nyanga). Very high levels of infestation are also noticed in areas in NR2 (Harare, Karoi, Chegutu, Rusape, Chinhoyi, Goromonzi) and NR3 (Mutoko, Gokwe, Chivhu) implying that these areas have the highest risk of *M. persicae* infestation. The districts in NR2 and NR3 have the largest crop producing areas due to climatic and terrain suitability therefore are conducive and prone to aphid presence at very high intensity. The model shows that the districts in NR4 (Masvingo) and NR5 (Chiredzi, Gwanda, Hwange) have low to no level of *M. persicae* infestation

respectively indicating a potentially lower risk of *M. persicae* infestation in these areas. These results indicate that regions in the southern lowveld have the largest areas that are not suitable for vegetable (i.e. tomato) production and hence are not favoured by *M. persicae* under the current climatic conditions.

5.3.3 Variable importance

The results of the study indicate the importance of the climatic variables in modelling the presence and absence of *M. persicae*. The most important variables are those with the highest mean decrease in accuracy (Fig 5.3). According to the RF model, the distribution of *M. persicae* was shown to respond to precipitation and temperature related factors although precipitation related factors were more significant compared to temperature related factors. Average annual precipitation (BIO12) was the best predictor of the distribution of *M. persicae* followed by precipitation of the wettest month (BIO13) then precipitation of the wettest quarter (BIO16). Temperature related variables that were of importance in determining *M. persicae* distribution was the temperature annual range (BIO7) and temperature seasonality (BIO4) (Fig 5.3).

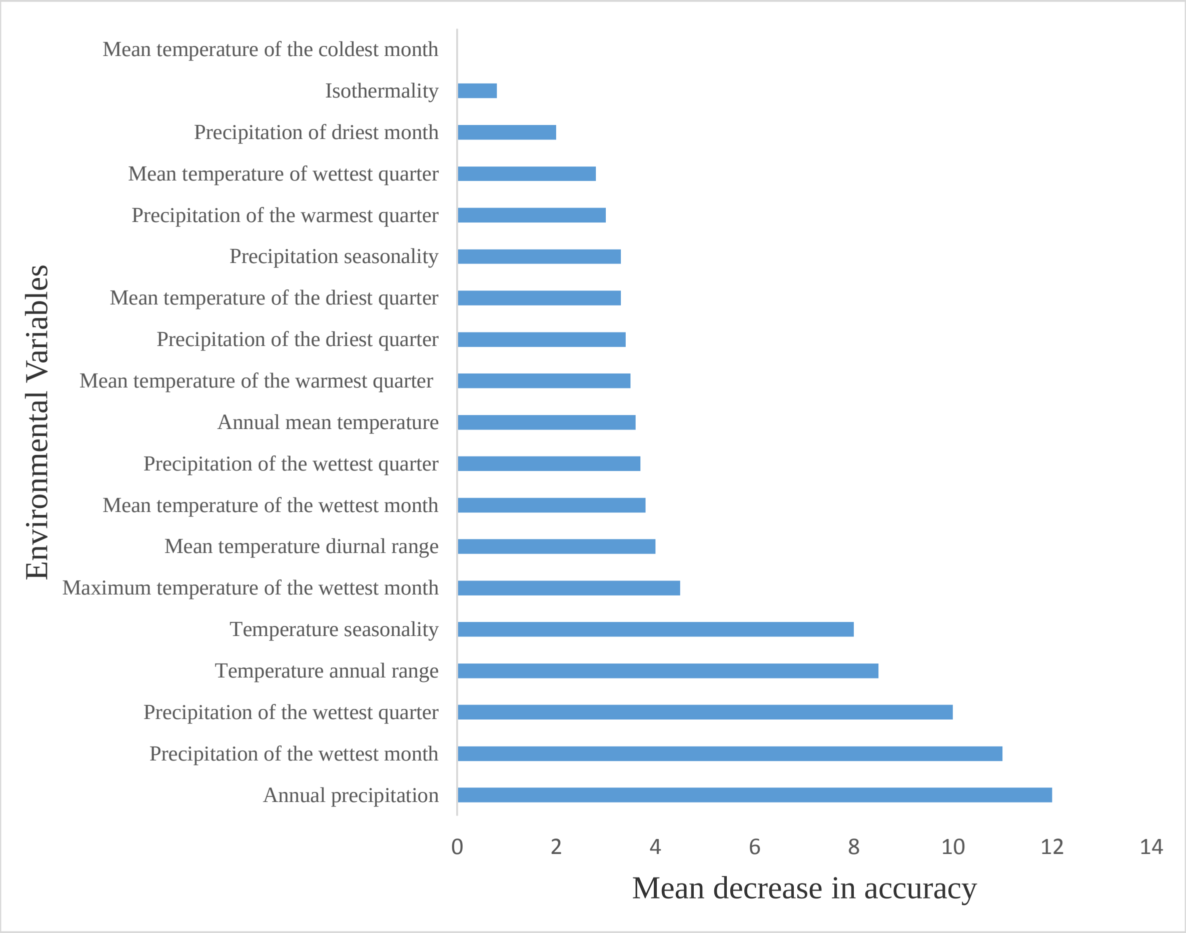

Fig 5.3: Importance of the environmental variables in the RF model.

Precipitation related variables influence the distribution of aphids more than temperature related variables.

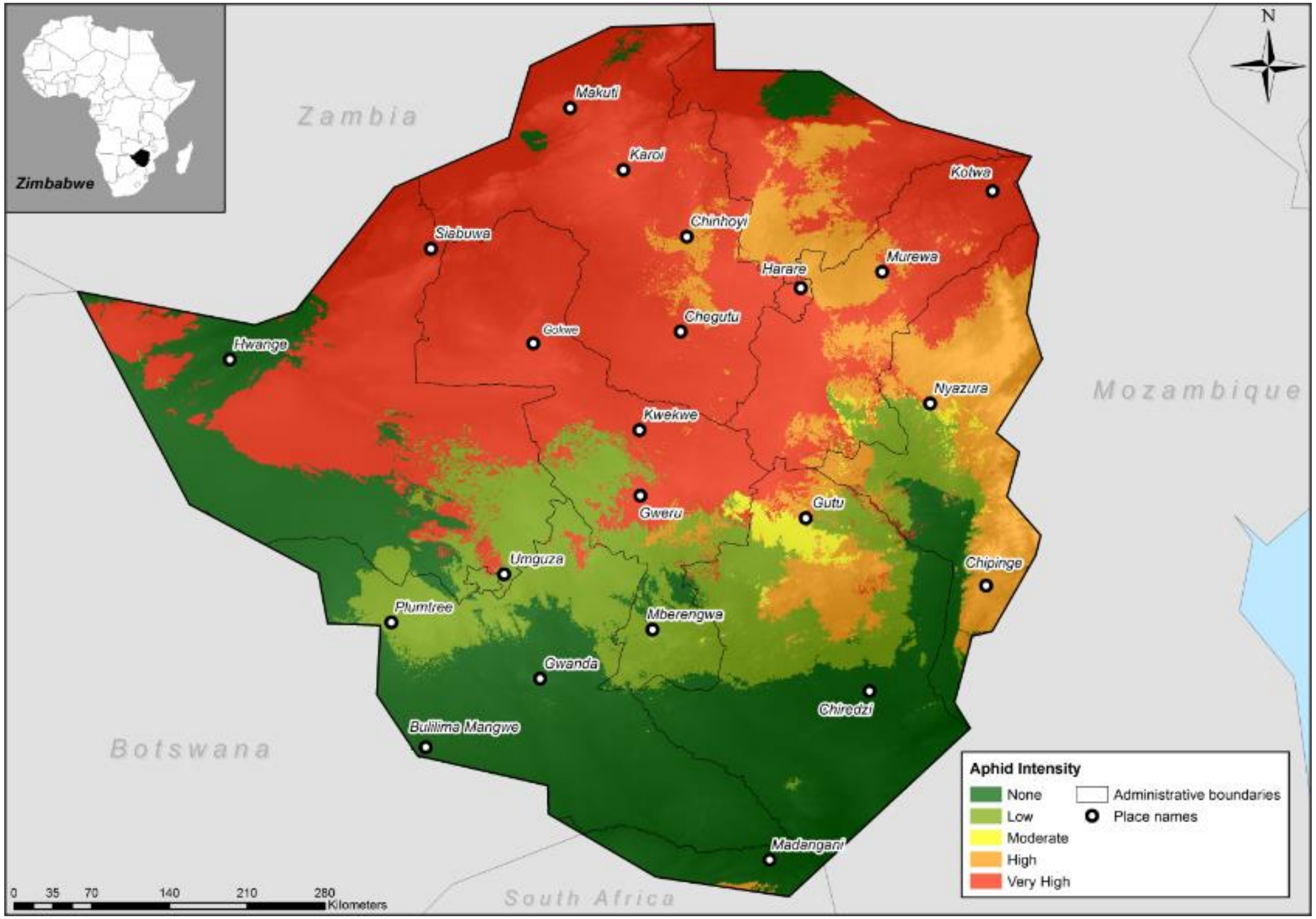

Fig 5.4: A national map showing the current levels of *M. persicae* distribution using the RF model. There are variations in the levels of *M.persicae* infestation depending with the agro ecological region

5.4 Discussion

This study combines field information collected from various agro ecological zones in Zimbabwe with bioclimatic data to model the distribution and level of infestation of *M. persicae*. Using a RF modelling approach, successful mapping accuracies were obtained during winter and summer over a two-year period. The outcome of this study would contribute towards the development of a national monitoring framework for the distribution of *M. persicae* as well as identifying target areas for insect pest management strategies.

Adam et al. (2011) found that the random forest was successful in mapping the distribution of insect pests similar to some studies that were conducted by Ismail et al. (2010) and Peerbhay et al. (2014). Adam et al. (2011) produced overall accuracies of between 76.92 and 81.54 and kappa values ranging from 0.53 and 0.63. Peerbhay et al. (2014), produced user's and producer's accuracies ranging between 60 and 100% and overall classification accuracy of 68.75%.

The RF model indicated that bioclimatic factors related to precipitation and temperature were the most critical factors influencing the distribution of *M. persicae* in Zimbabwe. Annual precipitation (BIO12), Precipitation of the wettest month (BIO13) and precipitation of the wettest quarter (BIO16) were found to be most important precipitation related factors while temperature annual range (BIO7) and temperature seasonality (BIO4) were the most important temperature related factors although precipitation factors were more important in influencing *M. persicae* distribution in Zimbabwe. This could have been as a result of the indirect effects of precipitation on the soil and water supply for the host plants (Moyo, 2000). The annual precipitation amounts are higher in the eastern highlands (Chipinge) and the Highveld (Goromonzi, Nyazura, Harare, Chegutu, Chinhoyi, Murewa) which is located roughly at the centre of the country and they decrease in mid altitude areas (Gweru, Kwekwe, Karoi). The lowveld (Chiredzi, Gwanda, Masvingo, Gutu), receives low amounts of rainfall while the low lying areas along the Zambezi valley to the north of the country receives a considerable amount of rainfall to encourage vegetation growth, however the topography and soil quality of the area are not suitable for crop production (Moyo, 2000). This supports the results of the presence and absence dataset which highlights the likely presence of the insect pest in the northern part of Zimbabwe compared to the southern part of Zimbabwe, where

provided the topography was even, the area along the Zambezi valley would be suitable for *M. persicae* presence on cultivated vegetables.
In this study, the differences in annual precipitation amount suggests that the areas which receive higher annual rainfall amounts and optimum temperatures for *M. persicae* survival and reproduction during the summer such as (Harare, Nyazura, Chegutu, Chinhoyi, Chipinge, Murewa) are more likely to be affected by *M. persicae* resulting in increased *M. persicae* infestation compared to lower rainfall areas (Plumtree, Mberengwa, Masvingo, Chiredzi, Hwange, Gwanda).

The wettest quarter in Zimbabwe is in most cases experienced in Zimbabwe between the month of January and the month of March while the wettest month is in most cases experienced in January. This suggest that there is increased breeding of *M. persicae* between the months of January and March as a result of increased crop production during this period and high rates of vegetation growth resulting from the Inter Tropical Convergence Zone (ITCZ) induced rainfall (Department of Meteorological services, 1981). These rains give rise to numerous alternative hosts during this period and a corresponding high *M. persicae* population. The levels of aphid infestation also decrease from the eastern part to the western part of Zimbabwe. This is as a result of precipitation quantities which decreases from the eastern part of Zimbabwe to the western part of Zimbabwe as a result of altitudinal differences (Department of Meteorological Services, 1981).

In the same study, the correlation studies revealed a significant negative association between increase in temperature and insect pest infestation which also correspond with the findings of this study where the hotter regions are potentially low *M. persicae* risk areas compared to the mild regions (Rahmathulls et al., 2012). In a study where temperature was simulated, Gillespie et al. (2012) found that the population of *Myzus persicae* was lower at temperature ranges between 32 and 40˚C while the optimum temperatures for the longevity of *M. persicae* were 21-27˚C and 30˚C was found to be the optimum temperature for reproduction of *M. persicae*. This therefore results in higher levels of aphids in the sub humid agro ecological regions compared to the semi-arid agro ecological region which experience temperatures in excess of 30˚C during the summer (Chikodzi & Mutowo, 2012).

The high levels of *M. persicae* infestation in areas such as Nyazura, Harare, Chipinge, Chinhoyi, Karoi, Mutoko compared with other areas might have been influenced by the climate and vegetation types and abundance these regions. In Chipinge, a variety of plantation crops, field crops, horticultural crops, flowers and forestry are produced in this agro ecological region. In areas such as Harare, Nyazura and Chinhoyi, there is intensive cropping of a wide variety of field crops as well as irrigated crops (Moyo, 2000). This could have encouraged the rapid multiplication of the *M. persicae* due to the availability of numerous alternative hosts for *M. persicae*. Bebber et al (2014) noted that as a result of a changing climate, the majority of areas that are active in crop production will be saturated by insect pests in the future (Bebber et al., 2014) including *M. persicae*.

5.5 Conclusions and recommendations

This study successfully mapped the distribution of the *M. persicae* across the different agro ecological zones using bioclimatic variables. The RF model was successful in determining and quantifying the distribution of *M. persicae* across Zimbabwe's Natural Region. Precipitation related variables, more specifically, the annual precipitation, precipitation of the wettest month and precipitation of the wettest quarter were found to be the most important predictors of *M. persicae* distribution. Temperature related factors such as annual range and temperature seasonality were also important in determining the distribution of *M. persicae* although they were less significant compared to precipitation related factors. According to the RF model, higher populations of *M. persicae* are most likely to be found in Chipinge, Goromonzi, Harare, Rusape, Mutoko and they decreased in areas that are characterised by low rainfall accompanied by extreme temperature conditions during the summer such as Masvingo, Mberengwa and Chiredzi districts. Current monitoring and management strategies by the government, extension and stakeholders involved in insect pest management should be focused mainly in areas such as Chipinge, Harare, Goromonzi, Karoi, Mutoko and Gokwe districts because of higher precipitation which is coupled with increased crop production, vegetation growth, good quality hosts and a corresponding high level of *M. persicae* abundance. Projection of future risks of the various agro ecological regions to some virus vectors is of importance to enable timely planning of management measures in the areas where the insects are expected to occur under future climatic conditions.

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CHAPTER 6

MODELLING THE CURRENT AND POTENTIAL FUTURE RISK OF WHITEFLY IN ZIMBABWE: *BEMISIA TABACI* IN A CHANGING CLIMATE

Abstract

The whitefly, *Bemisia tabaci*, Gennadius (Hemiptera: Aleyrodidae) is one of the most important insect pest of field, vegetable and ornamental crops in the warmer regions of the world. In Zimbabwe, *Bemisia tabaci* is likely to benefit from temperature increases resulting in changes in its distribution range thereby reducing crop productivity in some areas. An understanding of the role of climatic factors in the current and potential distribution of *Bemisia tabaci* and the corresponding disease transmission over time and space is of importance in targeting surveillance of the insect pest and the diseases that are transmitted by the pest. In this study, information related to the level of infestation was collected through field surveys in the five agro ecological regions of Zimbabwe. A statistical modelling approach using the Random Forest (RF) ensemble was applied on the current as well as the projected climate data obtained from the WorldClim database. Using this modelling approach, we relate present-day *Bemisia tabaci* infestation to current climate and then project the fitted climatic envelopes under future climate conditions. Results from the RF model indicate that precipitation and temperature related variables are more important in determining the current and the future risks of *Bemisia tabaci*. The conducive environment to *Bemisia tabaci* infestations seem to be persistent throughout the years modelled in Zimbabwe. It has the potential habitats in the northern areas of Zimbabwe with Kotwa, Gokwe, Kwekwe and Chegutu districts having the largest area more conducive under the current as well as the future (2050 and 2080) climatic conditions. The habitat range of Bemisia *tabaci* will decrease under future climatic conditions (2080) in the south eastern lowveld, the western parts of Zimbabwe as well as some areas in the Zambezi valley. The habitat range will increase in the areas south of Gutu district, south of Chiredzi and south of Magandani. Overally, the findings highlight the potential of current and future vulnerability of *Bemisia tabaci* infestation in Zimbabwe. These findings contribute towards a framework for informing whitefly surveillance at spatial and temporal ranges, development of early warning systems, and disease prevention in areas that will be more susceptible to *Bemisia tabaci*.

Keywords: present distribution, projected distribution, Random Forest, *Bemisia tabaci*

6.1 Introduction

Bemisia tabaci was found in China in 1949 and was not considered an important pest (Cho, 1949). It became important, when it was found in most provinces of China and become a severe pest of numerous field and ornamental crops (Luo et al., 2002). *B. tabaci* is one of the serious threats to field and horticultural crops that are cultivated in the tropical and subtropical climates around the world both in the green houses and the open fields (Alemangri et al., 2012). It is currently spread throughout the world as a result of the transportation of infested plant material, globalisation and modern agricultural practises (EFSA, 2013). *B. tabaci* impose serious damage to a range of important crops worldwide including cash crops, major food staple crops, grain legumes, fiber crops, vegetables and ornamental plants (DeBarro et al., 2011). Besides being polyphagous, also *B tabaci* became successful because they can also be carried along with plants on which they are only visiting (non-host plants) (EFSA, 2013). As a result, *B. tabaci* is therefore now considered as one of the 100 worst invasive alien species in the world (Global Invasive Species Database, 2016).

The negative effect of the *B. tabaci* on crop plants is as a result of both direct and indirect attack on crops (Thompson et al., 2011). Direct damage to the crops is caused through its feeding, which removes plant sap, resulting in stunted plant growth, especially in young plants. The sap sucking feeding habit results in several plant disorders, such as the silver leaf of squash, stem blanching, whitening of cruciferous vegetables, as well as irregular ripening of tomatoes. Indirectly, *B. tabaci* damage plants by causing the production of large amounts of sticky honeydew which is secreted during feeding. The honeydew may cover plants and stimulate the growth of sooty mold, thereby reducing the plant's ability to photosynthesise efficiently. In addition to the direct and indirect damage, *B. tabaci* also act as carriers of viral pathogens that can severely damage susceptible plants (Cathrin & Ghanim, 2014). *B. tabaci* have been found to be responsible for the transmission of over 200 plant viruses including Begomoviruses, Carlaviruses, Criniviruses, Ipomoviruses and Toradoviruses (DeBarro et al., 2011; Martelli et al., 2011; Navas-Castillo et al., 2011) which have resulted in serious economic losses in many parts of the world (Thompson, 2011). However, begomoviruses are the most important plant viruses that are transmitted, causing crop yield losses of between 20 and 100% (Cathrin & Ghanim, 2014). The losses resulting from virus transmission by the *B* *tabaci*, however far surpass the direct losses resulting from their direct feeding on the crops (Shi et al., 2014).

Environmental conditions have been reported to be the major abiotic factor affecting the population dynamics of insect pest species (Khaliq et al., 2014) including the *B tabaci*. In many parts of the world, *B. tabaci* populations are more prevalent, displacing the local insect pests (Jiao et al., 2013; Hu et al., 2011; Navas-Castillo et al., 2011). Previous distributions of the *B. tabaci* were confined to temperate climate zones but in the past two decades it has spread to every continent in the world except some areas in Europe and the Antarctica (Cuthbertson & Vanninen, 2015; EFSA, 2013).

Whiteflies by being ectothermic in nature, temperature plays a vital role in their survival and reproductive success (Cui et al., 2008). High populations of *B. tabaci* reach their peak during the summer season when temperatures are above 30˚C (Luo et al., 2002). However, in an experiment that was conducted in China, adult survival was significantly when temperatures exceeded 41°C (Cui et al., 2008). Food supplies was also found to play significant roles in the development and survival of *B. tabaci*. Salvucci (2000) found that with the availability of food, the sorbitol levels that protect proteins from heat stress are likely to increase. This implies that as long as the area invaded or occupied by whiteflies has hosts plants for the insect, they are able to survive and resist heat stress even if the temperatures are high.

Research on *B. tabaci* distribution has been conducted in developed countries such as Australia (Sutherst et al., 2011) and Europe (EFSA, 2013). In Europe, a lattice Permission-based Delegation Model (PBDM) was used to describe the population dynamics of *B. tabaci*. This model was used as a result of its ability to explain the phenomena in its pure form. Thus, the demographic processes of invasion can be explained from life history strategies described at the individual level (Gutierrez, 1996; Metz & Diekman, 1981). The model indicated that the range expansion by *B. tabaci* is predicted, particularly in Spain, France, Italy, Greece and along the Adriatic coast of the Balkans. However, even under the scenario of a 2˚C increase in temperature, northern European countries are not likely to be at risk of *B. tabaci* establishment because of limitations in climatic conditions (Gilioli et al., 2013). In most developing countries, little attention has been paid to the distribution of *B. tabaci* insect species (Gormley et al., 2011). In African countries such as Tanzania, *B. tabaci* was modelled using the “Climate envelope model”. This model was found to be useful in predicting the potential distribution of whiteflies in Tanzania. Using this model, it was found that the most suitable zones for *B tabaci* presence were located mainly in the north western side of the country, including part of the western side. The central and the southern regions, on the other hand, were not potentially suitable. Overall, it was found that the suitable ranges could increase in the future (Guastella, 2013). Considering the direct and indirect influence of insect pests to crop productivity, there is a need for studies to forecast the distribution of economically important insect pests under future climatic changes (Biber-Freudenberger, 2016).

Predicting and quantifying the current occurrence and potential distributions of established insect species is an important step in establishing surveillance monitoring and efficient management when the projected distribution of the pest is established (Gormley, 2011; Lodge et al., 2006). Projections of insect pests therefore facilitate better preparedness to reduce outbreaks of serious insect pests and hence yield losses by enabling the development of effective pest management strategies before the occurrence of the insect pest outbreak (Fand et al., 2014). It is within this context that the study was conducted to map the risk to *B. tabaci* infestation under current and future climatic scenarios across the various agro ecological regions in Zimbabwe.

6.2 Materials and Methods

6.2.1 Description of the study area

The study area is described in section 3.2.1.

6.2.2 Data on occurrence of the *B. tabaci*

Smallholder farmers that grow crops throughout the year and produce primarily tomato and brassicas were sampled for the purpose of this study. Data on the level of whitefly distribution was collected from the 5 agro ecological zones in the winter and summer seasons for 2015 and 2016 through sampling for *B. tabaci* on tomatoes and cabbages which are the preferred hosts of whiteflies. Ten tomato or cabbage producing sites in each agro ecological region were sampled in this study. At each site, ten sampling plots measuring 100m×100m were randomly used. At each of the sampling points, latitude and longitude coordinates as well as altitude was recorded using a Global Positioning System (GPS) model (Garmin e Trex Vista). More specifically, a hand lens was used for the sampling of *B. tabaci* at each sampling point. It was used to distinguish between empty pupal cases and live insect pests. Inspections of the undersides of lower leaves was used to detect the presence of some immature stages of the whiteflies but the adult whiteflies were used in this study because they were easy to see. *B. tabaci* were checked on the undersides of the leaf and on new growth on ten randomly sampled plants at each sampling point in the agro ecological region. Each location within an agro ecological region was separated by a distance of at least a kilometre. If the undersides of the lower leaves were covered with the whiteflies, adults would soon be seen near the top of the plants. There were five levels of whitefly distribution that were considered and these were measured mainly during the early morning when the whiteflies were inactive. In instances where no whiteflies were found on leaves it was recorded as none, 1-20 *B. tabaci* was recorded at low, 21-50 *B. tabaci* was recorded as moderate, 51-100 was recorded as high while >100 was recorded as very high.

6.2.3 Climatic variables

For the present and the projected climatic conditions, nineteen Bioclimatic (BIOCLIM) variables were contained from the WorldClim database (Hijmans et al., 2005). These were used as potential predictors of the whitefly distribution. The bioclimatic variables represent annual trends, seasonality and extreme or limiting environmental factors (Nix, 1986). These variables include, annual mean precipitation and annual mean temperature for Zimbabwe as well as information related to maximum temperature of the wettest month, minimum temperature of the coldest month, and precipitation of the driest and wettest quarters. The various climatic variables that were used in the RF are shown in Fig 6.1 which highlights the importance of each variable in the RF model.

6.2.4 Modelling approach

The random forest modelling approach was used in this study. The approach is explained in section 5.2.4. A map indicating the various points where the field survey was conducted is shown in Fig 5.1.

6.3 Results

6.3.1 Mapping the current distribution of *B. tabaci* using the bioclimatic variables

Using the test data set, the results of the current distribution of whitefly using the RF model are shown in Table 6.1. During the summer season, successful producer's and user's accuracies ranged between 50 and 100%. An overall accuracy of 75% was produced by the

RF model (*ntree* = 3500 and *mtry* = 2) for mapping the various levels of whitefly infestation during the summer season with a resultant kappa value of 0.67. In the winter season, the producer's and user's accuracies ranged lower from 33 to 100%. However, an overall classification accuracy of 65% was obtained with a kappa value of 0.57 (Table 6.1). These results indicate a higher reliability of the summer data compared to winter data in modelling the distribution of *B. tabaci*.

Table 6.1: Classification accuracies based on the level of infestation using the RF model for modelling the current distribution of *B. tabaci*.

	Summer		Winter	
	U A	PA	UA	PA
None	88	70	71	50
Low	50	100	33	100
Moderate	67	100	50	100
High	100	50	100	50
Very high	80	80	80	80
Kappa	0.67		0.57	
OA	75%		65%	

NB: UA refers to User's Accuracy, PA refers to Producer's Accuracy and OA refers to Overall Accuracy

A distribution map highlighting the risk of the *B. tabaci* is shown in Fig 6.1. The RF map showed that, districts such as Kotwa, Chinhoyi, and some areas along the central part of Zimbabwe such as Gokwe district have the largest crop producing areas that is suitable for the high occurrence of *B. tabaci* making the areas very high risk zones for *B. tabaci* infestation. High risk areas for the *B. tabaci* are mainly found in areas around Chipinge, Nyazura, Gweru and Harare districts. Areas around Gutu district have a moderate risk of whitefly infestation. However, areas to the south of Zimbabwe have a lower area that is suitable for crop production and shows a low risk of *B. tabaci* infestation. Chiredzi and the surrounding areas have been found to have the lowest area that is suitable for crop production and hence is unsuitable for whitefly distribution under the current environmental conditions.

6.3.2 Importance of bioclimatic variables in *B. tabaci* distribution

The most important bioclimatic variables that determined the distribution of *B. tabaci* was measured using the mean decrease in accuracy (Fig 6.2). *B.tabaci* distribution was shown to respond to both precipitation and temperature related variables. However, annual precipitation was of greatest importance in determining the potential spatial distribution of the whiteflies using the RF model compared to all the other bioclimatic variables. Annual mean temperatures were also shown to have a higher impact on the distribution of *B. tabaci*. The relative importance of the environmental variables are shown in Fig 6.2.

6.3.3 Mapping the future (2050 and 2080) distribution of *B. tabaci* using rainfall and temperature

Rainfall and temperature were shown to be the most significant variables in determining the current level of *B. tabaci* risk. Therefore, using these two variables, data for 2050 and 2080 were acquired from the WorldClim database and applied to the RF model for prediction. The results of the RF model on mapping the projected future (2050 and 2080) distribution of whitefly is shown in Table 6.2. The producer's and user's accuracies of the 2050 data ranged between 50 and 100% and produced an overall accuracy of 70 % with a kappa value of 0.62. For the year 2080, the producer's and user's accuracies ranged between 33 and 100% and a lower overall classification accuracy value of 65% was obtained with a kappa value of 0.55 (Table 6.2).

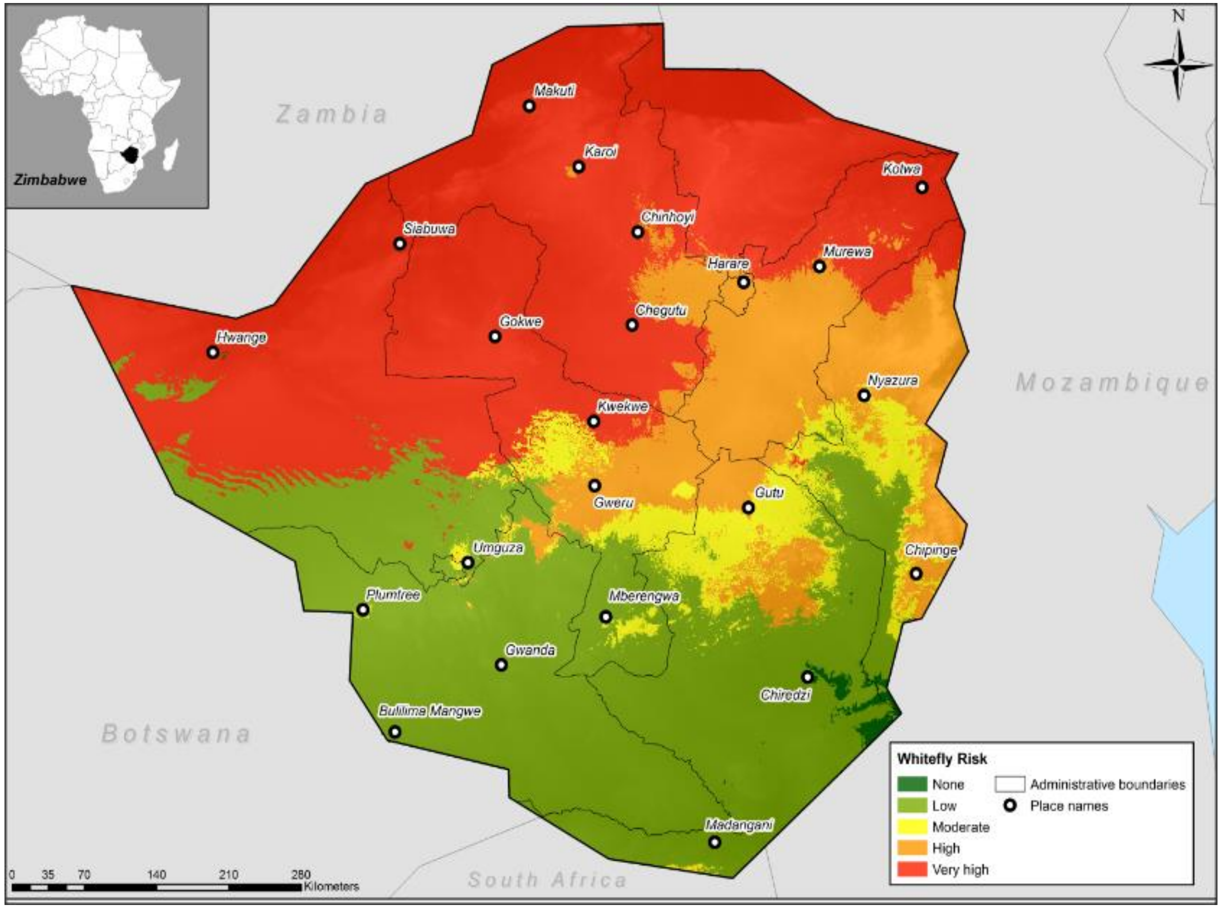


Fig 6.1: A map showing the current spatial distribution of *B. tabaci* in Zimbabwe**.**

There is high risk of *B. tabaci* to the north and central part of Zimbabwe compare to the Southern part

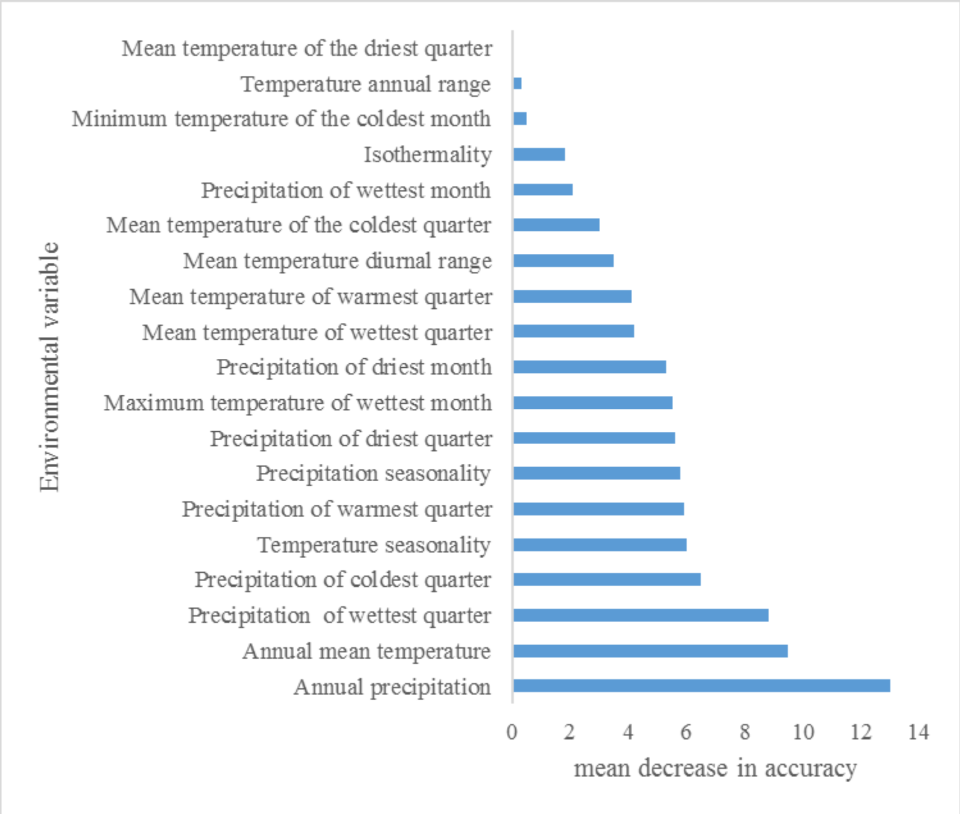


Fig 6.2 Importance of bioclimatic variables using the RF model.

Annual precipitation influences *B. tabaci* distribution compared to any other environmental variable.

Table 6.2: Final classification accuracies based on the level of infestation using the RF model for the year 2050 and 2080

	Summer (2050)		Summer (2080)	
	UA	PA	UA	PA
None	86	60	86	60
Low	33	100	33	50
Moderate	67	100	67	100
High	100	50	50	50
Very high	67	80	60	75
Kappa	0.62		0.55	
OA	70%		65%	

NB: UA refers to User's Accuracy, PA refers to Producer's Accuracy and OA refers to Overall Accuracy

The spatial distribution of whitefly under the projected climatic conditions in Zimbabwe indicated a general decline in the area that will be under very high risk in the northern parts of the country. Areas that will remain highly conducive for whitefly infestations between the present distribution and 2050 are areas around Gokwe, Kwekwe, Siabuwa, Chegutu and Kotwa. However, areas that are currently under very high risk such as Chinhoyi, Hwange and Murewa will shift from a higher risk to a lower risk by the year 2050. On the other hand, the areas that will be more at a higher risk to whitefly compared to the current distribution are the areas around Gutu, Umguza districts, south of Chiredzi and south of Magandani. The areas that will be at a lesser risk to whitefly by 2050 will therefore shift northwards from the southern part of Zimbabwe (Fig 6.3).

The distribution of whiteflies in Zimbabwe generally show a decline in areas that will be under very high whitefly infestation in the future when the RF model was used. By 2080, there is a projected expansion in the areas under low risk from whitefly infestation in the southern part of the country compared to the present distribution as well as 2050 distribution. In addition, there is also a likely decline of whitefly risk in some areas in the Zambezi valley to the north of Zimbabwe. In contrast, areas to the south of Gutu will at a higher risk to whitefly infestation by 2080 and also Hwange will be at a higher risk of whitefly infestation compared to the year 2050. Using the RF model, areas around Kotwa, Makuti, Siabuwa, Gokwe and Chegutu will remain highly susceptible to whitefly infestation by the year 2080 (Fig 6.5).

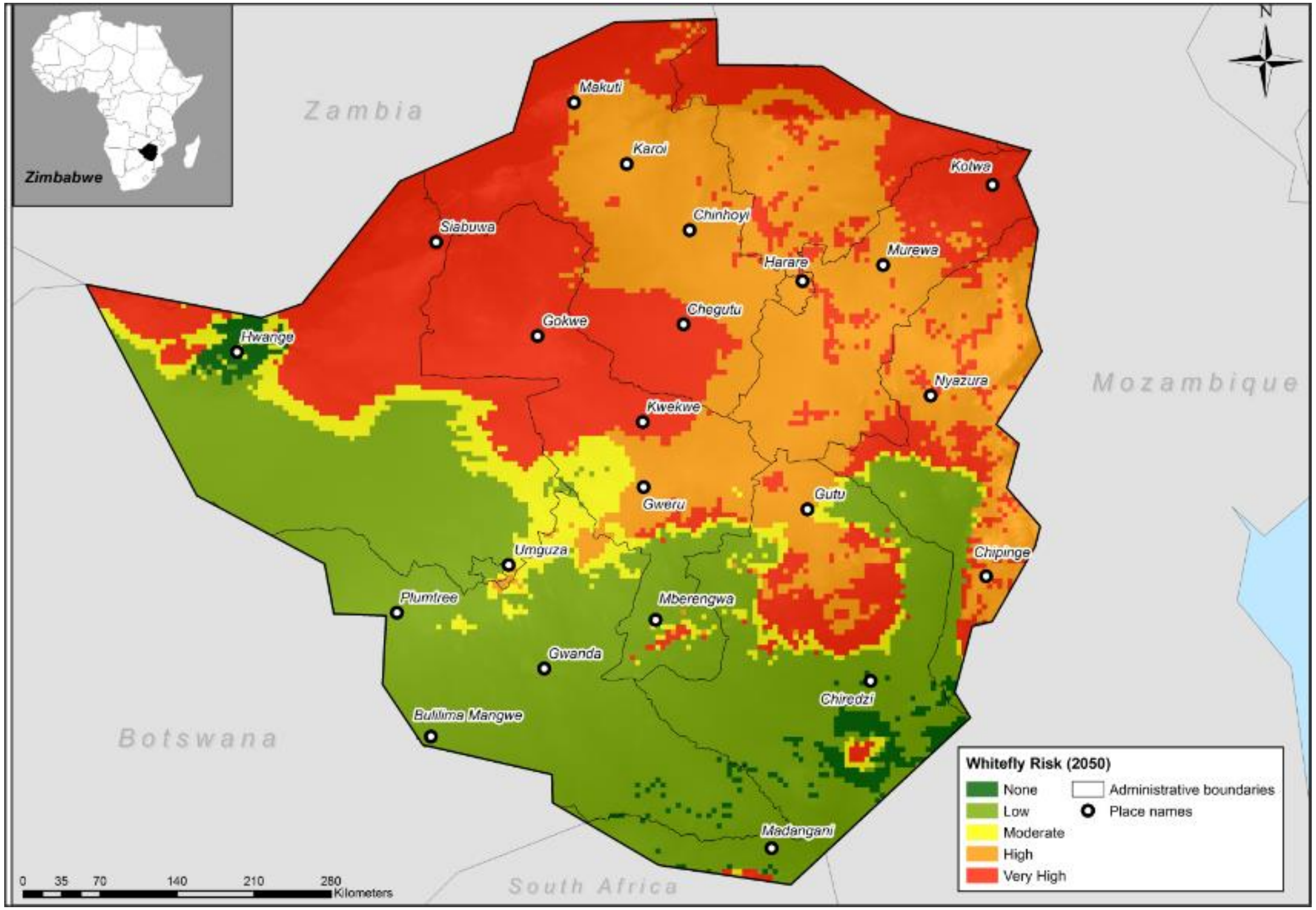
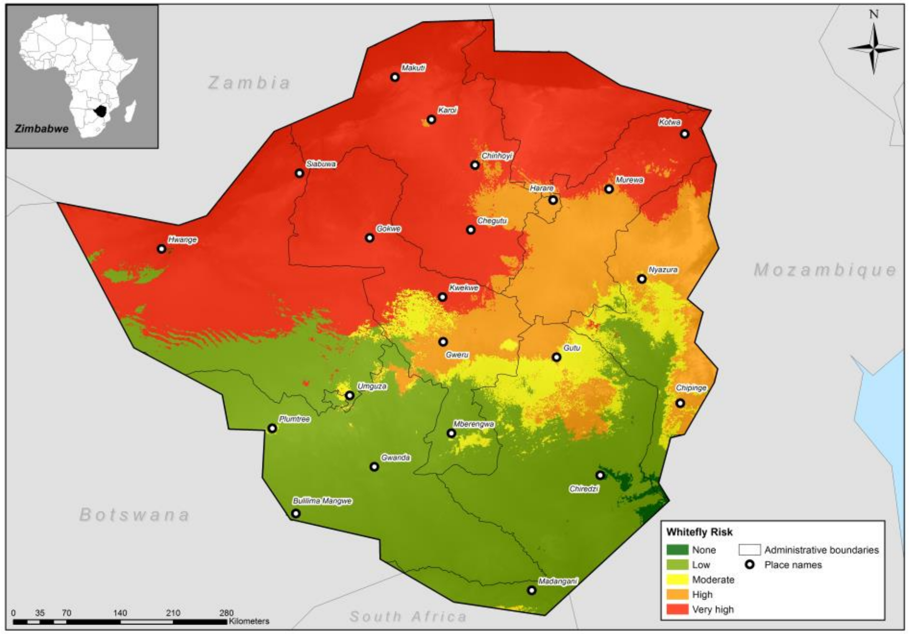
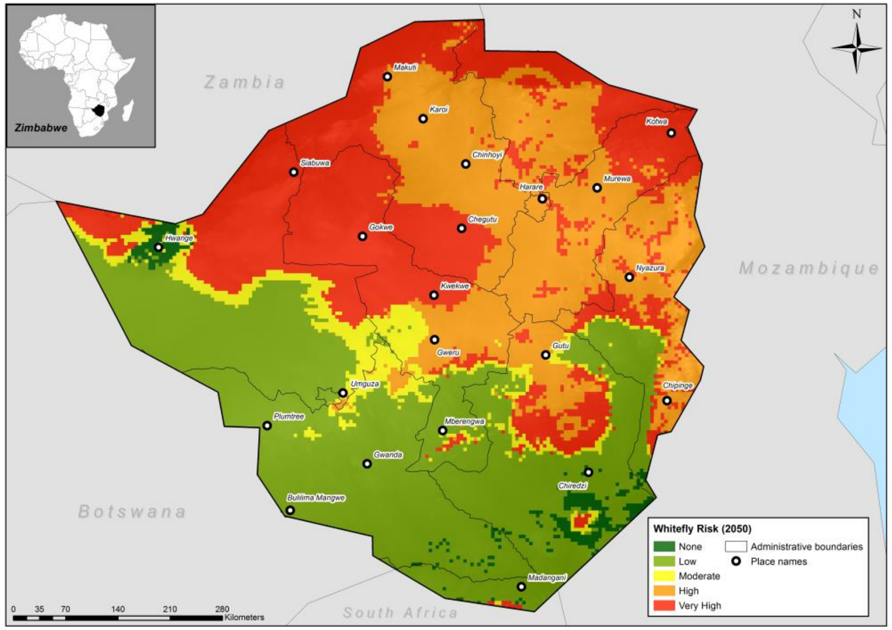


Fig 6.3: Projected *B. tabaci* distribution in Zimbabwe by the year 2050.
Some areas in the southern Lowveld will become susceptible to *B. tabaci* by 2050.



a) Current whitefly distribution



b) Whitefly distribution by 2050

Fig 6.4: National maps comparing *B. tabaci* distribution between the current distribution and the year 2050. The maps show an expansion of area under risk from *B. tabaci* between the current distribution and the year 2050.

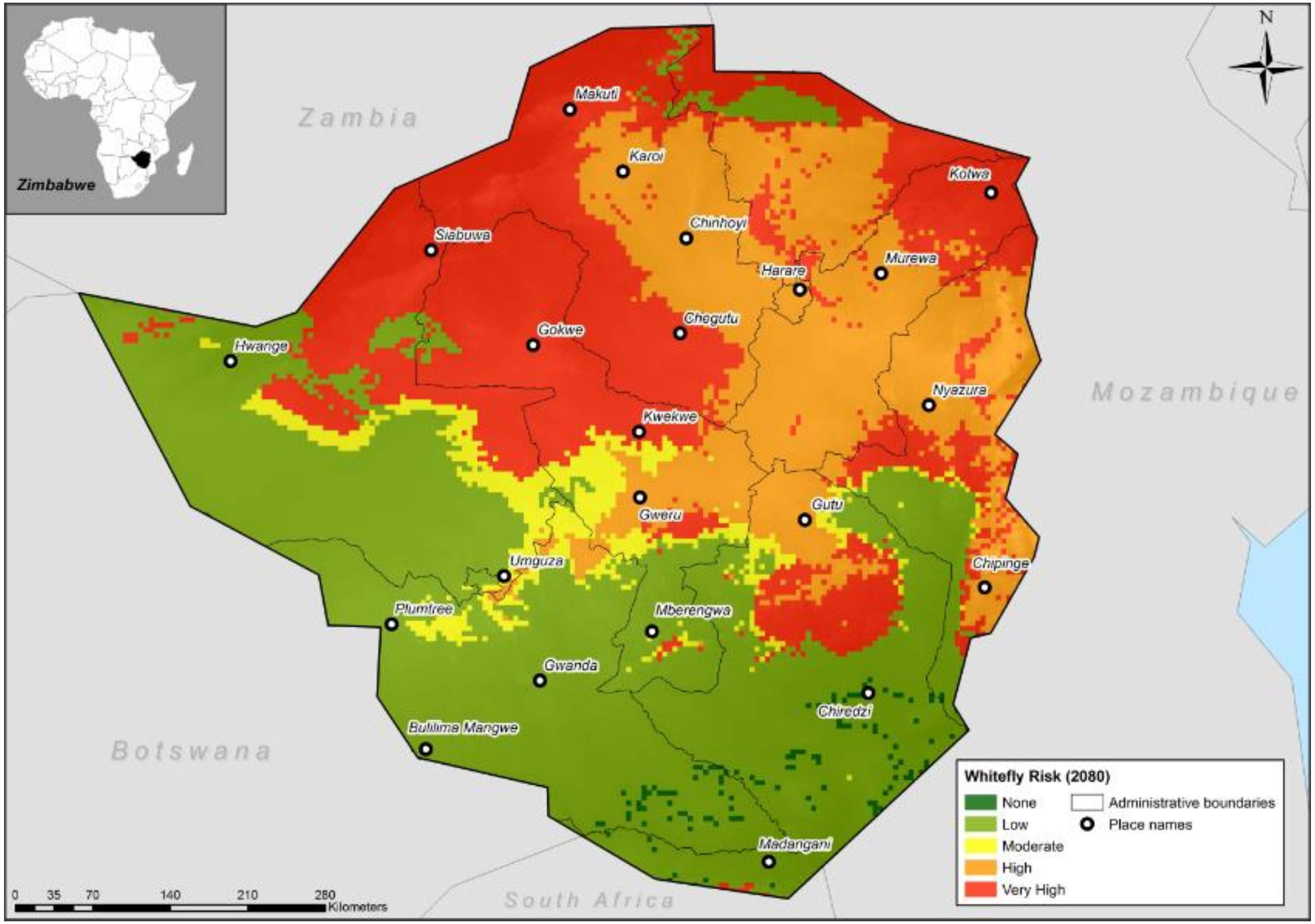
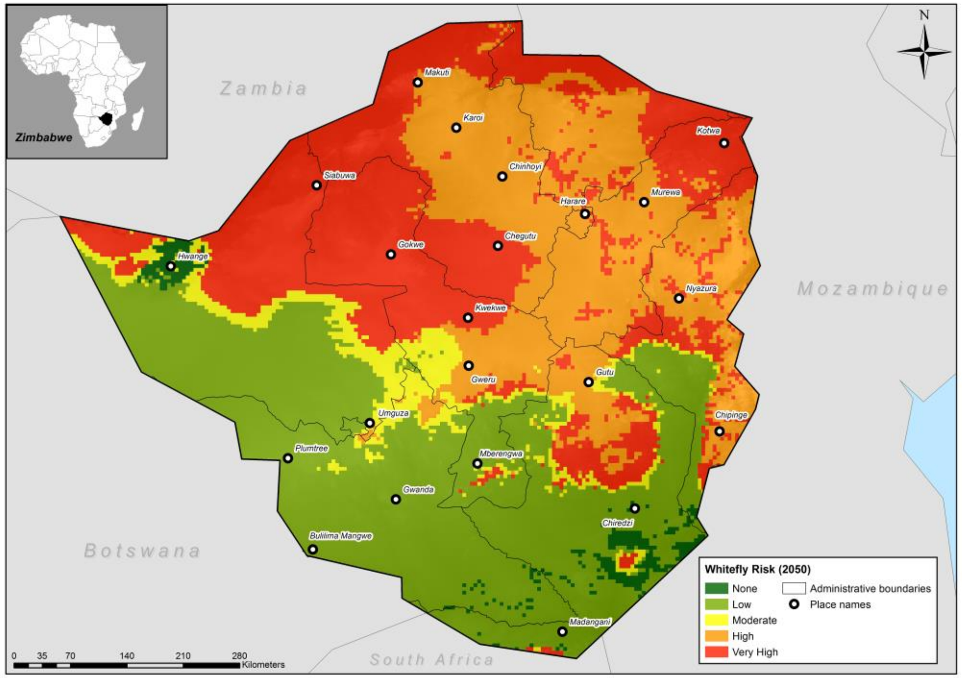
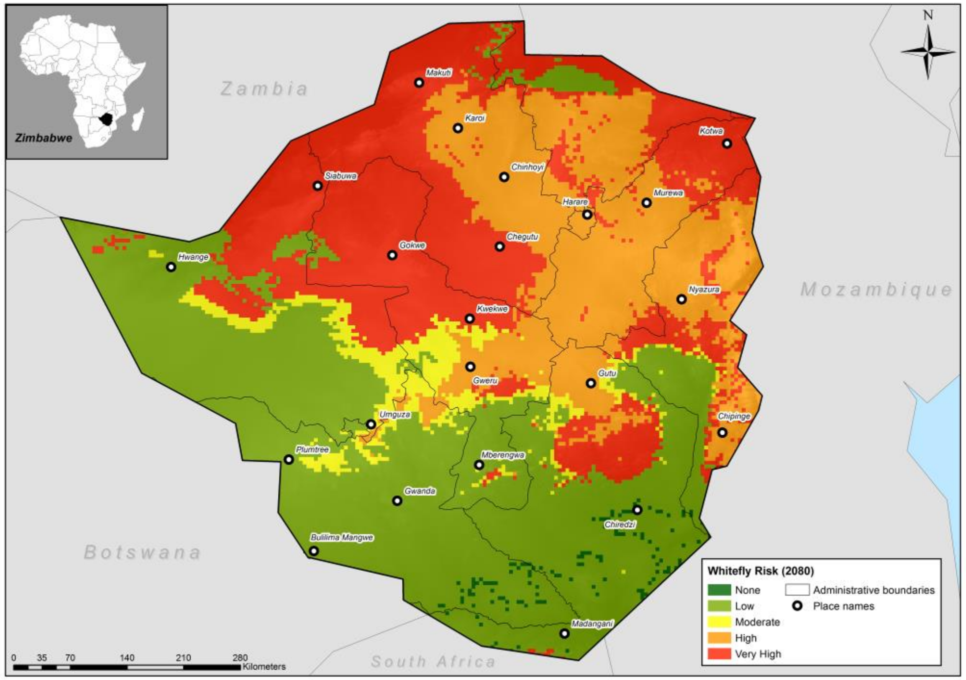


Fig 6.5: A national map showing the projected *B. tabaci* distribution by 2080.
Some places north of the country will be at less risk of *B. tabaci* by the year 2080.



a) Whitefly distribution by 2050



b) Whitefly distribution by 2080

Fig 6.6: National maps comparing *B. tabaci* distribution between the year 2050 and 2080.

The maps show that some places in the south eastern lowveld and the Zambezi valley will become less susceptible to *B. tabaci* risk between 2050 and 2080.

6.4 Discussion

This study used field data collected from various agro ecological regions of Zimbabwe to map current and future risk of whitefly infestations. Using the RF model, successful mapping accuracies were obtained for the present distribution of whitefly using the summer data set. The results of this study showed that the summer data set was more effective in mapping the distribution of the whitefly compared to the winter data set and hence the summer data set was used for the projected distributions. The efficiency of the summer data set could have been as a result of increased suitability of climatic conditions and host availability that are required for oviposition, reproduction, growth and longevity of whitefly during the summer season.

The random forest model was successful in mapping the distribution of the whitefly in this study and produced similar accuracies to that of other insect pest distribution studies that were conducted in South Africa (Adam et al., 2011; Ismail et al., 2010). In the studies that were conducted on forest insect pest species, overall accuracies ranging 68-82% were obtained while in this study overall accuracies ranged from 65% to 75% across all the periods modelled were obtained. However, there was a reduction in the overall accuracy with time from the current distribution to the year 2080.

From the findings of this study, the annual precipitation and the annual temperatures were found to be key determinants of whitefly distribution in the country. In addition, precipitation of the wettest quarter and precipitation of the coldest quarter were also found to be important predictors of whitefly distribution. In Zimbabwe, the wettest quarter is usually experienced between January and March (Kutywayo et al., 2013). This makes this period the most important time that is required for the emergence and the initiation of development of the whitefly. Higher annual precipitation is also indirectly important in increasing soil moisture thereby stimulating the growth of the host plants as well as the alternative hosts resulting in an increase in feeding, size, growth as well as the reproductive potential of the whiteflies (Simpson et al., 2012). The low rainfall that characterises the southern part of the country is therefore a likely contributing factor to low whitefly risk because of fewer susceptible host plants as well as poor quality host plants which indirectly affect the biology of the whiteflies and hence is abundance. The findings are in line with the study of Kutywayo et al., (2006); Kutywayo, et al., (2013); Chapoto et al., (unpublished) in their previous studies on coffee white stem borer and aphids respectively who observed that the distribution of these insect pests were more influenced by precipitation related factors as than the temperature related factors. The insect pests modelled were more likely to occur in areas which receive higher rainfall compared to lower rainfall areas. In a related study where *B tabacci* was modelled in cassava production regions in Tanzania, *B tabacci* was shown to have a higher probability of occurrence in those areas which were characterised by relatively high altitudes (1000–1300m) and annual mean temperatures of 24-26°C. Its distribution was concentrated in areas with a range of precipitation values of > 150 mm in March or April and characterised by yearly average annual precipitation between 750-1000 mm (Guastella, 2013) which is the case with Zimbabwe's areas in agro ecological region 2. The findings of Guastella (2013) highlights the importance of the precipitation of the wettest quarter in determining whitefly distribution.

The importance of the temperature as another major determinant of whitefly distribution was also observed by Jaramillo et al., (2011) and Jaramillo et al., (2009) who noted that temperatures were important variables that determined the distribution of the coffee berry borer. In this study, the districts that experience low precipitation and higher temperatures such as the south eastern lowveld were at a lower risk of whitefly infestation compared to the districts that receive higher rainfall and relatively lower temperatures. In a study that was conducted by Baoli et al., (2003), he showed that lower (<17˚C) and higher (>35˚C) temperature had a negative effect on the survival of .*B tabaci*. In the same study, he noted that *B. tabaci* had a longevity of 44 days at 20˚C and 10 days at 30˚C. This implies that the decrease in suitability of whitefly infestation in southern lowveld which experience temperatures in excess of 35˚C in the summer could have been as a result of climate change which exceed the temperature thresholds or the temperature windows that are required for the survival of the whiteflies resulting in the unsuitability of the area to the whitefly.

The decrease in whitefly risk in some areas of the country such as the south eastern lowveld as well areas such as Harare, Murewa, Chinhoyi, Karoi is also in line with a study that was conducted by Kutywayo et al., (2013), using the BRT and the GLM models which projected that the risk of the coffee white stem borer in Mutasa district would decrease by 2080. This could have been as a result of the changes in optimum conditions that are able to support the biology of the whitefly such as the changes in annual precipitation and the changes in the annual temperatures which could exceed the optimum or be reduced under future climate as a result of climate change and variability thereby reducing the level of whitefly risk.

The increase in the suitability of the area to the south of Gutu and west of Chipinge could also be due to some favourable environmental conditions which encourage productivity caused by a changing climate by the year 2050 and 2080 which have a possibility to encourage the reproduction, growth and survival of the whiteflies in this areas. These environmental conditions could be increased rainfall and more conducive temperatures that can be brought about by a changing and variable climate which supports vegetation growth (whitefly hosts) and hence increased whitefly populations (Ladanyi & Horvath, 2010).

6.5 Conclusions

The RF model that was used in this study was a useful tool in determining the current and projected infestation risk of whitefly by the year 2050 and 2080. The model indicated that precipitation related variables such as annual precipitation, precipitation of the wettest quarter and precipitation of the coldest quarter as well as the annual mean temperature were the important predictors of whitefly distribution. The model predicts that very high whitefly risk will persist in high vegetable production regions under the present climate as well as the future climates (2050 and 2080). Some areas that are currently not suitable for whitefly infestations will become suitable under future changes in climate such as the areas to the south of Gutu district, west of Chipinge, south of Chiredzi and south of Magandani. Areas that are at less risk to whitefly infestation are projected to shift from the southern part of Zimbabwe towards the central and the western part of Zimbabwe. From these results, there is need for development and application of environmentally friendly adaptation strategies to reduce the negative effects of whitefly especially in the regions where the whitefly is projected to increase. Preventative measures need to be put in place in the areas where whitefly is expected to occur in the future. Irrigation infrastructure and development need to be prioritised by the government in order to utilise the opportunity to increase vegetable and crop production in the southern areas of the country which are likely to be unsuitable for whitefly incidence under current and future climates. This creates an opportunity for vegetable production in the lowveld once irrigation and soil fertility options are improved because of the environmental conditions that are not conducive to whiteflies.

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CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Major findings

The changes in the climate as a result of increasing atmospheric gas composition have the potential to alter insect pest dynamics in tropical countries such as Zimbabwe. Most of the climate change studies that have been conducted in Zimbabwe focused on the impact of climate change on the yields of mainly cereals crops and the adaptation strategies to cope with decreasing yields in a changing climate. These studies have disregarded the likely impact of the changing climate on insect pests, which are an important determinant of crop yield under changing and variable climate conditions. This study was conducted to determine the response of insect pests to a changing climate in Zimbabwe from the farmer's perspectives across the five agro-ecological regions of Zimbabwe, determine the measures that are currently being adopted to manage insect pests in vegetable crops, to map the likely distribution of emerging insect vectors as well as to project the potential distribution of these insects under future climate scenarios. Questionnaires, key informant interviews, focus group discussions and the Random Forest modelling approach were used in this study.

The findings of this study revealed that farmers had the perception that increased warming, shorter winter seasons and changes in precipitation patterns are influencing the abundance, behaviour, physical appearance, distribution as well as the emergence of new insect pests in Zimbabwe. As a result of the milder winters that are currently being experienced in Zimbabwe, farmers in agro ecological regions 1, 2 and 3 (humid and sub humid climates) and regions 4 and 5 (semi-arid climates) have noticed a surge in insect pest population during the present winter seasons compared to the past winter seasons which were characterized by lower temperatures and lower insect pest incidences. Some respondents in agro ecological regions 4 and 5 (semi-arid climates) could not differentiate the changes in climate patterns compared to the farmers in agro ecological regions 1, 2 and 3. The farmers' perceptions to climate change were in line with the observations of the key informants such as the local leaders, the environmental management officers and extension officers who have observed an increase in the prevalence of insect pests and attributed their prevalence to changes in climate variables. The perception of the farmers were also in line with the meteorological data which highlighted variable precipitation trend and a positive trend in the annual mean minimum and maximum temperatures over the past years.

Insect pests such as the aphids, stem borers, cutworms, diamond back moths, leaf miners, bollworms and the whiteflies have been cited to be responding to the changes in the climate variables across the five agro ecological regions. Of the emerging virus vectors, aphids and whitefly were found to be the major insect vectors throughout the country, whose abundance was found to be significant throughout the year in agro ecological regions 1, 2 and 3 while in agro ecological regions 4 and 5, the prevalence of these insects was highlighted to be more pronounced in the winter seasons compared to the summer seasons.

In response to the increasing insect populations on vegetables, farmers adopted various measures of control. Indigenous measures which included intercropping of susceptible and non-susceptible crops, intercropping with crops which repel insect pests, use of trap crops, crop rotation to eliminate the specialist insect of a particular plant family as well as the removal of severely infested plants were used by the farmers. Besides cultural measures, there was an increased use of chemical insecticides by all the respondents. There were also increases in the insecticide doses, increases in the frequency of chemical insecticide application and the use of insecticide mixtures. Application of some insecticides that are not intended for food crops (highly hazardous) was also part of insect pest management strategies that were used by the farmers to control the high levels of insect pests in vegetable crops.

Using the RF modelling approach, it was shown that the distribution of the insect vectors, the aphid and the whitefly were mainly influenced by precipitation and temperature related variables. This resulted in the high levels of infestation in the northern half of the country and the eastern highlands where higher precipitation is received and relatively lower temperatures are experienced, compared to the southern half of the country which is characterized by extremely high temperatures and lower rainfall amounts. These extreme weather variables result in the areas becoming unsuitable for aphid and whitefly development as a result of limited vegetation growth which most likely affect host availability and the extreme temperatures which are unfavorable to the biology of aphids.

The susceptibility of Zimbabwe to whitefly occurrence was persistent in 2050 and 2080. Whitefly has the potential habitats in the northern areas of Zimbabwe while the central part will be less conducive to the development of whitefly infestations by the year 2050. By the year 2080 the levels of whitefly will further decrease in the lowveld, the central and the western parts of Zimbabwe. The habitat suitability will increase in areas such as south of Gutu district and west of Chipinge. The results of the study highlight the potential use of the vulnerability maps to inform whitefly surveillance at both the spatial and temporal ranges.

7.2 Implications

The results of this study results imply that the changes and variability in climate are likely to alter the abundance, the distribution and the status of insect pests in Zimbabwe. Some insects that were formerly minor pests such as the aphids on maize crops will become key pests of maize in the future. The breakdown of natural control measures such as the natural enemies resulting from chemical insecticide overuse as well as the changes in climate will further aggravate the insect pest problem in the country leading to severe insect pest outbreaks, crop losses and food insecurity.

The increase in the insect pest populations in the country will expose the farmers and consumers to insecticide hazards as a result of the overuse of chemical insecticides in trying to control the increasing insect populations. There is therefore urgent need to address the problem of insecticide overuse by utilizing other non-chemical insect pest control strategies.
The response of the insect pests to changes in precipitation and temperature variables and the resultant changes in dynamics in the various agro ecological regions of the country require the government to implement control strategies in the areas where the insect pests are currently occurring. Public awareness, preventative strategies in the areas or regions where the insect pests are projected to occur in the future will reduce crop losses as a result of insect pest and disease attack.

7.3 Recommendations

- Integrated insect pest management (IIPM) which involves a combination of control measures such as biological, physical, mechanical, minimal use of chemical insecticides and the use of bio pesticides should be promoted and advocated for by the various agents such as the extension officers, NGOs and farmer organizations. IIPM is of importance in reducing over reliance on chemical insecticides thereby minimizing environmental and health hazards whilst at the same time reducing the chances for the development of insecticide resistance and further surges in insect pest population.
- Breeding for crop genotypes that resist insect pest attack can also be done especially for crops whose leaves are not the consumable parts. Leaves that have trichomes, leaves that contain defensive compounds and pubescent leaves need to be included in breeding programs to reduce insect pest attack on the crops. Research on yield attributes of these resistant crop varieties need to be done so that the farmers are aware of the challenges and opportunities of using these improved genotypes compared to the measures that are being currently used to control insect pests.
- Determining the current distribution of some major insect pests of crops should also be done to enable the development of a national monitoring and surveillance framework for insect pest distribution. Modelling will be of importance in reducing the magnitude of insect attack if preventative control measures are to be put in place well before an insect pest outbreak occurs.
- Government intervention through insect surveillance at a spatial and temporal scale, throughout the agricultural production regions and development of early warning systems to increase farmer awareness and relevant stakeholders of crop insect pest outbreaks is of importance. Supporting farmers to control insect pests through prevention will help to reduce crop losses as a result of insect pest attack. Policies to reduce overuse of insecticides and promoting the use of alternative insect pest control strategies especially in the regions which are likely to be suitable for insect pests in a changing climate is of significance.

7.4 Future research

- Research on the influence of various precipitation levels on the biology of insect pests need to be conducted to determine the direct and the indirect influence of precipitation levels on insect abundance and distribution since most of the research that was conducted focused on the influence of temperature. Little research was done on the effect of precipitation levels on the biology of insect pest. Most of the work on precipitation concentrated on plant pathogens. However, from this study, precipitation was also found to be a key driver of insect pest distribution in the country, therefore further analysis is required.
- Studies to evaluate the effect of temperature on the biology of the insect vectors under tropical conditions need to be conducted to determine how the insect vectors will respond to the increasing temperature conditions in terms of the number of generations per season.
- A national monitoring framework for the distribution of important insect species to target the behavior, life cycle and distribution of the major insect pests need to be conducted so that intervention strategies can be developed to target the most susceptible growth stages of the insect pests.

APPENDIX 1

QUESTIONNAIRE: RESPONSES OF INSECT PESTS TO A CHANGING AND VARIABLE CLIMATE IN ZIMBABWE: FARMER PERSPECTIVES.

My name is Rumbidzai Debra Chapoto and I am a PhD student working on a research topic entitled "Responses of insect pests to a changing and variable climate in Zimbabwe: Farmer perspectives". I am kindly asking for perceptions on how insect pests are influenced by the changes in climate. May you kindly assist freely with your views and comments. All the information collected here will be treated with strict confidentiality and it is only for the purpose of academic research.

Instructions: Please tick √ where applicable and fill in where there are spaces

1. Gender of the respondent: 1. Male ☐ 2.Female ☐
2. In which natural region are you? NR 1☐ NR 2 ☐ NR3 ☐NR4☐ NR5 ☐
3. Are you aware of a changing climate in Zimbabwe? 1. Yes ☐ 2. No ☐
4. What are the indicators of a changing climate in your region?
   1. Late rainfall
   2. Long dry spells
   3. Erratic rainfall
   4. Shortened rainy season
   5. Increased frequency of droughts
   6. Shortened cold season
   7. Increased frequency of floods
   8. Other............................Specify..
5. Which insects is a major crop insect pest in your agro ecological region?
   1. Bollworms
   2. whiteflies
   3. Aphids
   4. Cutworms
   5. Armyworms
   6. Red spider mite
   7. Beetles
   8. Termites
   9. Other............................Specify..
6. Which crop do you produce mainly in this agro ecological region?
   1. Maize

2. Tobacco
3. Cotton
4. Tomatoes
5. Sorghum
6. Vegetables
7. Other..Specify...

7. In which season are these weeds most dominant? 1. Summer ☐ 2.Autumn ☐

3. Winter 4. Spring ☐ 5.All year round ☐

8. Is there a change in the population of the insect pests over the last 30 years? 1. There is an increase ☐ 2. There is a decrease ☐ 3.There is no change ☐

9. If there is an increase in number of insect pests, what factors do you think have led to increased incidence of these insect pests?
   1. Shortened winters
   2. Warmer winters
   3. Increased dry spells
   4. Insect pests resistance
   5. Poor insect pest management
   6. Low rainfall
   7. Other ....Specify...

10. Which season of the year are these insect pests most prevalent?
    1. Summer ☐ 2.Autumn ☐ 3. Winter ☐ 4.Spring ☐
    5. All Year round ☐

Insect pests' biology, physiology

11. How do you perceive the problem of insect pests with respect to the following attributes in the past 30 years:

Behaviour: 1.They have increased mobility
2. They are generating young ones very fast
3. Many pests are now flying
4. They are becoming too crowded even on older leaves

Physical appearance: 1. They have developed different colour variations
2. They have generally become lighter in colour
3. They have generally become darker in colour
4. Many of the pests have developed wings

Symptoms they cause: 1.Yellowing of the whole leaves
2. Mottling-green mixed with yellow and white colour
3. Stunted growth-slow growth
4. Blackening of leaf veins
5. Asymmetry of leaf lamina
6. Brown spots
7. Leaf roll
8. Line pattern on the leaves

12. How many different types/forms of the most problematic insects pests highlighted on question 5 have you noticed in your fields during the past 10 years?

Problem insect	Different types/forms of the same insect
a) Bollworms	
b) Aphids	
c) Armyworms	
d) Cutworms	
e) Red spider mite	
f) Beetles	
g) Other	

Can you comment on the responses of aphids to a changing climate in Zimbabwe..
....
....
....
....

Thank You!!

APPENDIX 2

QUESTIONNAIRE: FARMER KNOWLEDGE OF CLIMATE CHANGE IMPACTS AND ADAPTATION STRATEGIES IN THE MANAGEMENT OF VEGETABLE INSECT PESTS IN ZIMBABWE.

My name is Rumbidzai Debra Katsaruware-Chapoto and I am a PhD student working on a research study entitled "Farmer knowledge of climate change impacts and adaptation strategies in the management of vegetable insect pests in Zimbabwe". I am kindly asking for your knowledge, opinions and information pertaining to the various strategies that are used by the smallholder farmers to manage the increasing abundance of insect pests of vegetables in a changing climate in Zimbabwe. Feel free to answer to the questions. The information gathered here will be treated with utmost confidentiality.

Instructions: Please tick √ where applicable and fill in where there are spaces

13. Gender of the respondent: 1. Male ☐ 2.Female ☐
14. In which natural region are you? NR 1 ☐ NR 2 ☐ NR3 ☐ NR4 ☐ NR5 ☐
15. Are you aware of a changing climate in Zimbabwe? 1. Yes ☐ 2. No ☐
16. What are the major climate induced challenges to vegetable production in a changing climate?
    9. Droughts
    10. Vegetable insect pests
    11. Plant diseases
    12. Weeds
    13. Other............................Specify...
17. Which insect is a major vegetable pest in your agro ecological region?
    10. Bollworms
    11. Aphids
    12. Cutworms
    13. Armyworms
    14. Red spider mite
    15. Beetles
    16. Diamond Back Moth
    17. Other............................Specify...
18. How do you view the extent of crop losses from insect pest and disease attack on your vegetables?
    1. It is high
    2. It is moderate
    3. It is low

19. Which crops are mostly attacked by these insect pests?

1. Rape
2. Cabbages
3. Kale
4. Tomatoes
5. Butternuts
6. Spinach
7. Other.......................................Specify..

20. Which major strategy do you use to control insect pests of vegetables?

1. Insecticides
2. Biological
3. Cultural
4. Integrated Insect Pest management

21. Are the chemical insecticides effective in the control of the insect pests?

1. Yes ☐ 2. 2. No ☐

22. If No, give reasons to your answer on question

....

....

23. How frequent do you spray these chemical insecticides?

1. Once/month ☐ 2. Twice /month ☐ 3.Once /week ☐ 4.Twice /week ☐

5. Other, please specify..

24. Is there a difference in spraying frequency from what you used to do in the past years?

1. Yes ☐ 2. No ☐

25. Do you mix these chemical insecticides? 1. Yes ☐ 2. No ☐

26. Besides the chemicals which other measure do you use to control insect pests?

Strategy	**Please tick**
Rotation	
Intercropping	
Removal of heavily infested plants	
Use of trap crops	
Sorghum	

vegetables	
Onions	

27. Giving names, explain the role played by named natural enemies in the control of the insect pests
    1. Ladybirds
    2. Lacewings
    3. Spiders
    4. Big eyed bugs
    5. Parasitic flies
28. Are these natural enemies effective or their efficiency has been reduced over the past years?
    1. They are effective ☐ 2. They are less efficient 3.☐ 3. There's no change ☐

29. What do you think could be the reason for a reduction in efficiency of the natural enemies?
    1. They are becoming fewer
    2. They can't feed on the big insects
    3. They have developed many hosts
    4. Natural enemies are overwhelmed by aphid population
30. Aphids have become a problem in all vegetable growing areas of the country. What do you think?
    1. Strongly agree ☐ 2. Agree 3.neutral ☐ 4. Disagree☐
    5. Strongly disagree ☐
19. If aphids are an important insect pest, in which crops are the aphids most prevalent?
    …………………………………………
    …………………………………………
20. What corresponding diseases or symptoms are caused by these aphids?
    1. Yellowing
    2. Mottling/mosaic symptoms
    3. Brown spots
    4. Stunted growth
    5. Curling of crops
    6. Death of plants
21. Who provides you most information of managing insect pest population in your agro ecological region
    1. AGRITEX
    2. NGOs
    3. Fellow farmers

THANK YOU!!!