A Spatial Suitability Assessment of Maize and Tobacco in Response to Temperature and Rainfall Changes in Zimbabwe

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Declaration

I know the meaning of plagiarism and declare that all of the work in the dissertation, save for that which is properly acknowledged, is my own. I have referenced all quotations and other ideas borrowed from others.

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Abstract

Climate is changing, and this change poses threats to the agricultural sector. The impacts of climate are expected to become more extreme as the earth warms, and this change will affect climate suitability for different types of crops. The degree to which an increase in temperature patterns and rainfall variations will affect climate suitability for agricultural practices needs to be further understood. This can be achieved by performing a climate sensitivity analysis and contribute to informing adaptation policies and mitigation measures. This study aims to analyze the sensitivity of important crops in Zimbabwe, maize, and tobacco, in response to changes in temperature and rainfall patterns.

This research paper used a sensitivity analysis of climate variables; rainfall, and temperature, using historical climate data derived from WorldClim for the period 1990-2018 to assess climate suitability. The historical climate data was used as the baseline to assess the sensitivity of maize and tobacco under a 2°C, 3°C, and 4°C temperature increase as well as a 5%, 15%, and 30% increase and decrease in annual average rainfall amount. The modified spatial climate data was computed in QGIS, and suitability was simulated using the Ecocrop model embedded in the DIVA-GIS user platform. The results from this study indicated that in Zimbabwe, both crops are more sensitive to rainfall changes than to temperature changes (independently). A 5%, 15%, and 30% decline in the average rainfall will result in previously suitable areas becoming marginal, very marginal, and others unsuitable for both crops that are in agro-ecological regions I to III; i.e., provinces that include Mashonaland Central, Mashonaland West, Mashonaland East, Harare, and Manicaland. When crops are subjected to combined changes (temperature and rainfall), both crops become more sensitive. When exposed to high temperatures and low rainfall together, for instance, provinces such as Mashonaland Central, Mashonaland West, Mashonaland East, and Harare which are known as historically suitable areas for maize cultivation, will become marginal or very marginal. This change in suitability could have consequences not only on food security but also on people's livelihood and understanding the crops' sensitivity to climate changes helps support the well-being progress of the country.

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Chapter 1: Introduction

1.1. Background

1.1.1. Climate change and increased food demand

Climate is changing, and it has potential impacts on food security in terms of accessibility, utilization, and availability on the economy (FAO, 2017). Changes in climate and its variability is believed to be a result of anthropogenic processes, and the global surface temperature has already increased by an estimated 0.85 (0.65 to 1.06) °C from 1880 to 2012 (IPCC, 2014). By the mid-21st century, temperatures are projected to increase by about 3–5°C, while precipitation amount and intensity are also projected to change (IPCC, 2014). A warming of 1.5–4°C by 2100 will likely affect the agricultural sector by reducing crop yield and revenue across the regions (Hijmans et al. 2001). Moreover, the available Global Circulation Models (GCMs) suggest that temperature increases for Africa will reach 1.7□C by the 2030s, 2.7□C by the 2050s, and 4.5□C by the 2080s under RCP8.5 (Givertz et al., 2019; Climate change knowledge portal). Thornton et al. (2011) notes that the effects of a +4◦C warmer world could have disastrous effects without appropriate adaptation measures.

Like soil parameters, land-use and land cover, climate through rainfall and temperature is a significant driver of the suitability of a given region to a specific variety of crops (Fraga et al. 2016). Despite technological advancements such as plant breeding, irrigation, and in-field water harvesting for increasing production, climate remains a significant factor in agricultural production (Munamati and Nyagumbo, 2010). The agricultural sector is amongst the most vulnerable sectors in a changing climate yet, agriculture is the basis of human survival in a world where the population is continuously increasing (Mandal et al., 2020). The combined climate stress to maintain food production, and increased demand due to increased population, makes designing of the future crop production system even more challenging.

Globally and regionally, climatic patterns are projected to become more variable compared to the present patterns, including variations in frequency and severity of extreme climate-driven events such as cyclones, floods, hailstorms, and droughts (IPCC, 2014). More significant climate variability directly brings fluctuations in crop yields and supplies, thus threatening food security

(Alliance of the Consultative Group on International Agricultural Research (CGAIR) Centres, 2009). Shifts have already been observed in plant phenology and ecosystems in response to environmental change (Studer et al., 2007). In response to climate change, other plants are growing faster, which often decreases the quality and quantity of yields (Orlandini et al., 2009). Changes in climate patterns may lead to shifts in the geographical distribution of suitable climates for various crops. Also, in the absence of adequate adaptation measures, Southern Africa could face widespread negative climate change impacts in the agricultural sector, although these impacts would vary widely by crop (Lobell et al., 2008). Increasing temperatures and a decline in rainfall have already resulted in parts of Sub-Saharan Africa becoming unsuitable for several staple crops, which may result in the need to turn to more drought-resistant crops to ensure food security (Chapman et al., 2020). Several studies have shown that Zimbabwe is facing the effects of climate change in terms of rainfall variability, extreme climate events, and warming trends which are projected to reduce rainfed agriculture suitability (Brown et al., 2012; Unganai, 2009; Mugiyo et al., 2018).

1.1.2. Maize and Tobacco in Zimbabwe

Future changes in temperature and precipitation directly impact food production and the economy across the African continent (Niang et al., 2014) since many agricultural lands in Sub-Saharan Africa are rainfed. Growing areas of maize and tobacco are expected to face a yield reduction of 12%-40% by the 2050s. The climate suitability of these major crops is also projected to shift as the earth warms (Zabel et al., 2014; Rippke et al., 2016). Each crop thrives within a specific climate parameter that can be manipulated; however, climate change is expectedto alter these parameters and, inevitably, the geography of crop suitability (Travis, 2016).

Maize *(Zea mays L)* and tobacco (*Nicotiana tabacum L.*) crops are essential crops in Zimbabwe (Basera, 2015). Maize is a major food source and is ranked the third most important crop in the country (Nadiezhaet al., 2017), while tobacco is a major export crop accounting for foreign revenue (Ruckert et al., 2022). FAO (2012) showed that agriculture accounted for a significant percentage of formal employment, and over 70% of Zimbabwe's population is dependent on agriculture. Food security in Zimbabwe is basedon maize availability which is the staple food crop likely to be affected under projected changes in temperature and precipitation (Lunduka et al., 2019). Maize is a strategic crop whose productionmust be maintained at sufficient levels to enhance food security and self-reliance at both householdand national levels. An early study on the impacts of climate change on rainfed maize productionin Zimbabwe demonstrated that marginal areas would become very marginal and less suitable forgrowing maize because of variations in rainfall patterns (Makadho, 1996). Mhizha (2010) further notes that the projected rainfall variability will likely make rainfed maize production unstable.

On the other end, tobacco generates foreign revenue for the country and contributes around 10% of the country's GDP (Muir Lerescher, 2006). Tobacco is an important foreign currency earner contributing about a quarter of all export earnings, thus making the crop a major component of the country's GDP (Woelk et al., 2001). The tobacco crop is economically significant, and its value differs from country to country. The difference pertains to the nature of supply and demand (Woelk et al., 2001). Of all countries producing tobacco worldwide, countries like China, Brazil, India, the United States, Indonesia, and Zimbabwe dominate production (Shahzad et al., 2018), further showing how it is an important crop in the country. Zimbabwe was the 6th largest producer and third- largest tobacco exporter growing over 182 000 tons out of the world's total of nearly 6.2 million tons (Woelk et al, 2001).

Many Zimbabwean smallholder farmers are diversifying into tobacco farming as it is perceived as profitable and could potentially improve their ways of living and food security status (Chivuraise, 2011; FAO, 2012; Mutami, 2015). This is still the case although the profitability part has been negatively impacted by the economic situation of Zimbabwe. Tobacco is a significant source of income, lessening household poverty, improving rural farmers' livelihood, and at the same time making use of less fertile landthat could have been left unused otherwise (Chivuraise et al., 2016; Ngarava, 2020). The tobaccoindustry also generates significant employment for a considerable population (Zimbabwe TobaccoAssociation, 2013). Hence, tobacco has become an essential agricultural crop in Zimbabwe. Makarau and Zhakata (2000) noted that Zimbabwe's tobacco production has dropped by 4% in recent years, and the crop is one of the crops projected to be affected by climate change. Given its value to the economy and livelihood, it is crucial to understand how climate change will affect thedistribution of tobacco production areas to influence policymaking (Chemura et al., 2013). This is because, carrying out a climate sensitivity analysis for an important crop such as tobacco enables policymakers to draft informed policies on how to manage the crop sustainably.

1.1.3. Problem statement

In their Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) noted that the changing climate will likely modify the distribution of suitable climates for crop cultivation worldwide (IPCC, 2014). Climate change is projected to make Zimbabwe drier and warmer (Simba et al., 2012). As climate conditions change, the areas of suitability for growing maize and tobacco may shift. This projected change will likely negatively impact Zimbabwe's rainand temperature-sensitive agricultural sector (GoZ, 2010). Those changes affect not only food production but also the socio-economic situation of the population, as agriculture is not only a sourceof food but also a source of income for many African countries, including Zimbabwe. Zimbabwe,where most of the land is occupied by agriculture, will likely face reduced crop production due to low yield (GoZ, 2010).

To improve food security and inform adaptation decisions, it is crucial to understand how climate change will affect the agricultural sector, whether through staple subsistence crops (e.g., maize) or trading cash crops (e.g., tobacco). Conducting a climate suitability analysis to examine how sensitive these crops are to a changing climate is crucial. Few studies have analyzed crops' suitability sensitivity to changes in climate, while most have focused on assessing the impact of climate change on the cultivation patterns of several crops using mechanistic models (Ngwira et al., 2014). Some studies explore crop growth requirements in response to climate change for example, Lane and Jarvis, (2007); Adornado et al., (2008); Monterroso Rivas et al., (2011); Bonfante et al., (2015); FAO, (2017); Chikodzi, (2016); Zhang et al., (2017). Others focus on crop suitability based on climate variability in the future (Egbebiyi et al., 2019) and land suitability (El Baroudy. 2016; Gao et al., 2021). Hence, this study aims to assess the sensitivity of maize and tobacco suitability in Zimbabwe in response to level changes in temperature and rainfallto contribute evidence to improve future food security in Zimbabwe.

1.2. Rationale

The common information from numerous studies is that climate change could increase the existing problems in developing countries where communities are heavily dependent on the natural environment and rainfed agriculture (Chagutah, 2010; Zhao et al., 2016). Climate is a significant determinant of agricultural productivity therefore, to establish sound agrarian policies, policy makers and planners need to understand the potential impacts of climate change on the climate suitability for different crop types (Holzkämper, 2010; Chikodzi, 2016). In addition, the knowledge of the potential climatic patterns under current and future climate conditions is critical for policymakers to make adaptation and mitigation measures against the effects of climate change (Jayasinghe and Kuma, 2019) and capitalize on any beneficial results.

Without quality evidence, in terms of climate suitability and change distributions, efforts for increased productivity could remain ineffective and possibly counterproductive. Understanding climate suitability helps project whether suitable areas for specific crops are increasing, decreasing, or fragmenting in response to climate change (Jayasinghe and Kuma, 2019). Because the distribution and the abundance of crops can be affected by climate change, climate suitability analysis can better inform management decisions. In this research, the maize (*Zea mays L.*) and tobacco (*Nicotiana tabacum L.*) crops were considered because maize forms the staple food of over 95% of the country's population (Zimbabwe's Initial National Communication, ND), while tobacco plays a significant role in the country's economy.

A countrywide suitability assessment offers evidence for adequate planning and sustainable utilization of resources now and in the future (Zomer et al., 2008). At the same time, the analysis of climate suitability allows the identification of limiting factors of crop production, enabling decision-makers to develop plans for increasing productivity (Halder, 2013; Chen, 2014). This paper shall assess the climate suitability of maize and tobacco under a temperature increase by 2°C, 3°C, and 4°C, because they lie within the projection margins (3–5°C projections by IPCC (2014), independently and in combination with +/-5%, +/-15%, and +/-30% annual rainfall changes from the historical amounts.

This study will help provide information for the development of adaptation and mitigation strategies for maize and tobacco production under climate change conditions and help determine which areas will remain suitable for the two crops. Such climate suitability projections are essential to ensure sufficient food production and continuous tobacco production to sustain the Zimbabwean economy. Moreover, assessing the effects of climate changes on agriculture could help to adequately anticipate and adapt to maximize agricultural production (Costa et al. 2009). It is, therefore, necessary to carry out studies on assessing the spatial climate suitability of maize and tobacco in Zimbabwe in response to climate change to assist policymakers to find ways of addressing food insecurity and better the population's livelihoods in Zimbabwe. This is because the recurrence of droughts and threats posed by climate change requires improved methods of estimating crop production, particularly in countries dependent on rainfed agriculture and more vulnerable to food shortages (Kandji et al. 2006).

Indirectly, it could also help municipalities and communities to better understand the impact of the changes to equip them with the knowledge of adaptation strategies for planning. The accessibility to climate information has the potential to enable communities to make informed decisions in the face of global challenges (Stone and Meink, 2006). Hence the results from this research will help provide valuable information directly to policymakers, and indirectly to municipalities, and communities.

1.3 Aim

The aim of this study is to assess the sensitivity of maize and tobacco suitability in Zimbabwe, in response to level changes in temperature and rainfall.

1.3.1 Objectives

Despite the importance of maize and tobacco, there is relatively limited documentation of the future climate suitability. As a step towards filling this research gap, the objectives of this study are:

1. To investigate the spatial suitability of maize and tobacco under historical average climate conditions in Zimbabwe.

2. To perform a spatial analysis of suitability resulting from increased average temperature by 2°C, 3°C, and 4°C.

3. To perform a spatial analysis of suitability resulting from a 5%, 15% and 30% decrease, and 5%, 15% and 30% increase in the annual average rainfall.

4. To spatially analyze the resulting suitability sensitivity to the combined variations of temperature and rainfall.

Chapter 2: Literature Review

This chapter defines and presents the concepts of climate change, climate change in Zimbabwe, food security globally and food security in Zimbabwe.

2.1 Climate change

FAO (2008) defines climate change as, "*a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period, typically decades or longer*". This change in climate is triggered by increases in carbon dioxide, methane, and nitrous oxide concentrations in the atmosphere (Solomon, 2007). As a result of climate change, the Earth has been warming since the mid-century, already visible through the melting of glaciers and permafrost, decrease in the amount of snow, and high prevalence of extreme events such as droughts, among other factors (Nakicenovic and Swart., 2000; Rosenzweig et al., 2007; Rohde et al., 2013; IPCC, 2014).The temperature increases are most likely to affect developing countries largely dependent on rainfed agriculture (Givertz et al. 2019). The global mean temperature has risen since 1850, and a warming trend has been observed in the temperature records taken over the land, seas, and oceans (Solomon, 2007). Several studies have made projections of different degrees of change in average temperature and precipitation using different time periods, Representative ConcentrationPathways (RCPs), and climate models (Mounkaila et al., 2015; Barry etal., 2018). Figure 1a. below shows the global and regional risks for increasing levels of global warming and Figure 1b. shows the reasons for concerns; Impact and risk assessments assuming low to no adaption. Future projections indicate the possibility of extreme weather conditions for temperature (IPCC, 2022) relative to the period 1850-1900. These projections have been made possible using climate models, and despite the downscaling uncertainties, the models can provide useful information on changes in zones of agricultural productivity (Wheeler and Braun, 2013).

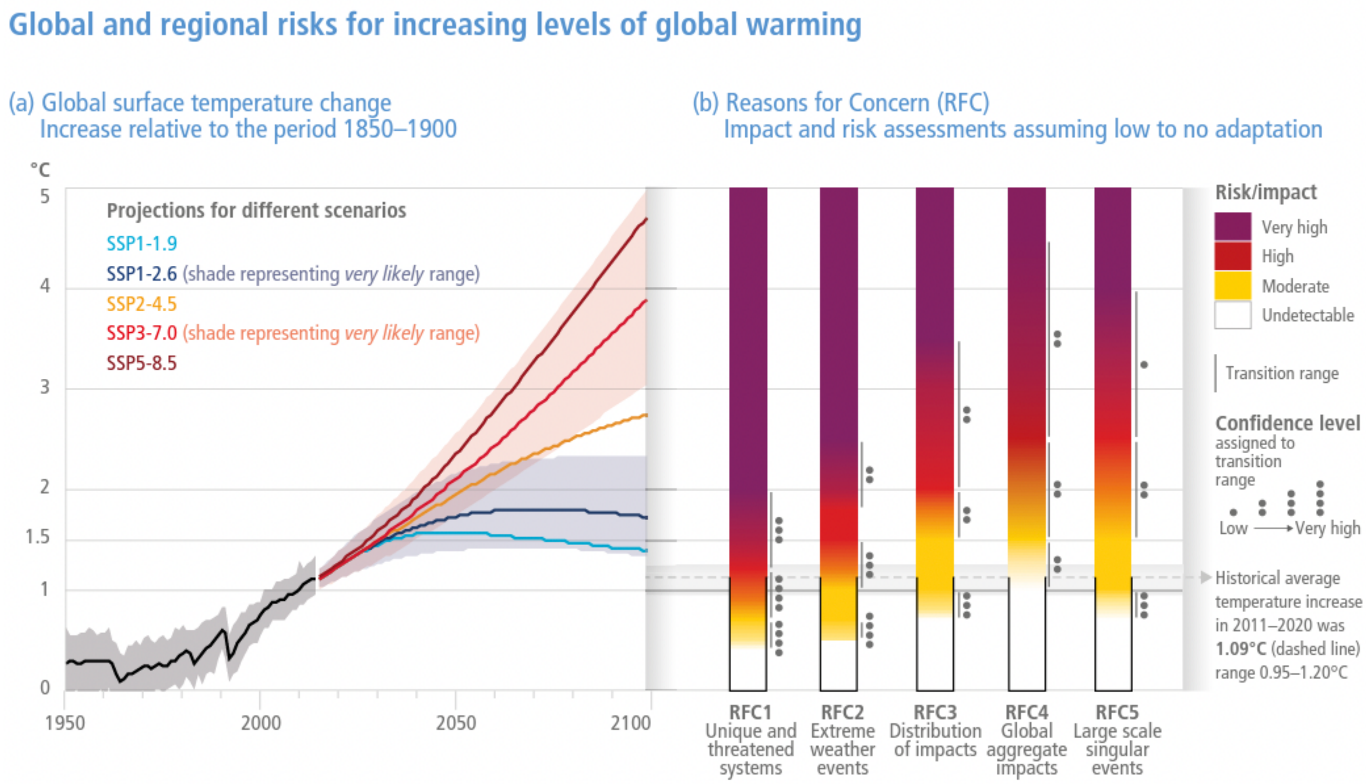


Figure 1. Global and regional risks for increasing levels of global warming (Pörtner et al, 2022)

Climate change is a challenge facing humanity (Brazier, 2017; Mupakati, 2017). This change is projected to bring disadvantageous effects, including increased frequency of high-temperature events, reduced amounts of precipitation, and other extreme events such as droughts reducing plant growth (Tester and Langridge., 2010). This climate change is expected to affect crop yield by changing growth duration, and other phenological parameters. In the tropics, under the projected extreme climate conditions, several crop varieties would unlikely produce because, crops in these regions are susceptible to climate change and climate variability (Byjesh et al., 2010). Wheeler et al., (2013) noted that climate change would magnify food insecurity in areas that are already in need, meaning that countries facing burdens of hunger to date are the same countries projected to be impacted by a decline in crop productivity. Therefore, climate change will potentially jeopardize the vision of a world without hunger (which is one of the Sustainable Development Goals) as it might affect the stability of the food systems (Tester and Langridge., 2010).

2.1.1 Climate change in Zimbabwe

Historic precipitation shows that a significant part of Africa is becoming drier (Josephine, 2007; Hartmann et al., 2013; Salerno et al, 2019). Southern parts of Africa, including Zimbabwe, show a decrease in precipitation (Mutekwa, 2009). The impacts of climate change will vary spatially, and it is projected to impact crop yield negatively, especially in the tropical regions where these declines are already being felt in the global agricultural production of maize (Lobell et al., 2011). Zimbabwe will be affected due to itseconomic status and the existing burdens, including poverty and diseases (Nadiezhda et al., 2017).Developing countries' contribution to climate change (in terms of greenhouse gas emissions) canhardly be accounted for (Brazier, 2017; nevertheless, they will likely suffer more from the impacts of climate change compared to developed countries (Oxfam, 2007).

Africa is projected to experience a rise in temperature of at least 1-2^{o}C s with a higher likelihood of extreme weather (Mulenga et al., 2017; Hamadudu, 2019), as illustrated in Figure 1 above. An early study by Unganai (1996) is a popular reference used to understand changes in climate that have occurred in Zimbabwe. The author confirmed that climate has been characterized by irregular rainfall patterns associated with extreme precipitation events and drought, shifts in the onset of rainfall, and increases in the frequency and intensity of seasonal dry spells (Unganai, 2009). As a semi-arid country, Zimbabwe is often affected by natural droughts, which are partly influenced by the El Nino-Southern Oscillation that originates from the Pacific Ocean (Brazier, 2017). Records for Zimbabwe indicate that since 1888, severe droughts have been recorded in the years 1911 to 1914, 1946 to 1947, 1960 to 1961, 1982 to 1983, 1991 to 1992, 1994 to 1995, 2002 to 2003, and 2006 to 2007, 2015 to 2016 and 2018-2019 (Chigodora, 1997; Unganai, 1996; Ndlovu, 2009; Frischen et al., 2020). These droughts are becoming more intense, directly affecting the country's economy (Ndlovu, 2009). For instance, the 1982-83 drought led to a loss of currency and millions in direct agricultural production and drought relief costs (GoZ, 2010). The drought from 1991 to 1992 resulted in the country's Gross Domestic Product (GDP) falling by 8% (Chimhou et al., 2010). With the effect of the changing climate, the country's seasonal rainfall has been fluctuating at a decreasing rate around a long-term trend. As a result of climate change, droughts are expected to become more prominent,affecting the country's food security (Zimbabwe's National Climate Change Response Strategy (ND).

In Zimbabwe, average temperatures were expected to increase by 3°C compared to 1960-1990, according to different global circulation models (Christensen et al., 2007), and rainfall was projected to decrease by between 5% and 18% mainly in the southern part of the country (Brazier, 2017). The shift in Zimbabwe's agro-ecological zones could be a result of climate change (Brown et al., 2012; Mugandani et al., 2012). Mugandani et al., (2012) also estimated a rise in the daily minimum and maximum temperatures by 2.6°C and 2.0°C, respectively. Several studies have also shown a decline in the annual mean rainfall over Zimbabwe (Rekacewicz, 2005; Chamaille-Jammes et al., 2007).

The country's economic dependence on available water, especially during drought years, has already suffered a decline and is expected to further decline under future climate (GoZ, 2010). A combination of low rainfall and low production has often resulted in large populations suffering from chronic malnutrition and food insecurity (Fischer et al., 2005). An early study on the impacts of climate change on rainfed maize production in Zimbabwe showed that marginal areas would become very marginal because of a decrease in precipitation (Makadho, 1996). For example, Nadiezhda et al. (2017) note that large areas in Zimbabwe that are currently suitable for maize cultivation will suffer from heat stresses and negatively impacting crop yields. However, the study of climate suitability for crop growth offers valuable information in the construction of sustainable and efficient adaptation measures in the Zimbabwean context. Other factors will play a role in response to climate change (e.g., improved technology, increased population, drought-resilient varieties).

2.2. Global food security

The Food and Agriculture Organization (FAO, 2017) refers to food security as a situation when all people have access to stable, sufficient, and nutritious food that meets their needs and preferences. In other words, food security means that everyone has physical, social, and economic access to adequate food that meets their dietary requirements. In 1948, the Universal Declaration of Human Rights made the right to food a key element of an adequate standard of living (Assembly, 1948). However, the negative impacts of climate change have been threatening this right. Nelson et al., (2009) suggested that climate change could lead to increased prices for crops such as rice, maize, and wheat, consequently leading to a fall in the consumption of cereals. Knowing that most

Sub-Saharan African countries' economies depend on agricultural systems, they will have to come up with ways to adapt their mostly rainfed agriculture (FAO, 2018), which is already under strain. Agriculture remains a primary source of employment and income for Southern Africa Developing Community's (SADC) rural population, with small-scale farmers contributing significantly to the annual yield (Basera, 2015). Adaptation will be a significant component of human survival with the changing climate.

In tropical regions, the agricultural sector is vulnerable to the impacts of climate change (Smith et al., 2014), and Sub-Saharan Africa is among the areas facing food insecurity worldwide (FAO et al., 2018). Sub-Saharan Africa is known to be highly vulnerable to climate change due to its relianceon rainfed agriculture and low adaptive capacity (IPCC, 2014; Mashizha, 2019). Rising temperatures are projectedto shorten the length of the growing season for several crop varieties in both arid and semi-arid areas (Calzadilla et al., 2013; Teixeira et al., 2013), while extreme temperatures can damage crops,thereby exposing these regions to possible food insecurity. This change in climate parameters may affect the ability of individuals to utilize food resources effectively by changing the conditions forfood security (Schmidhuber et al, 2007).

Climate change is projected to negatively impact the agricultural sector (World Bank, 2013). Erratic rainfall patterns coupled with droughts are a clear factor of agricultural production deficit, often followed by periods of food insecurity and economic losses (Frischen et al., 2020). The Sub-Saharan African region is projected to suffer from food insecurity due to a reduction in the cultivation land area, which is likely facilitated by unfavorable climatic conditions (Lane and Jarvis, 2007) as well as activities such as urbanization (Nellmann, Eds., 2009). In Sub-Saharan Africa, food security is most likely to be affected, and this is attributed to poor social and economic governance aligned with the projected impacts of climate change (FAO, 2017). To date, future climate suggests a likely decrease in crop yields, simultaneously affecting food security and exposing Africans to poverty, hunger, and malnutrition (Schmidhuber et al, 2007; Egbebiyi et al., 2019).

Population growth is affecting food security, and when coupled with the impacts of climate change, an increase in food consumption and a global increase in food demand becomes inevitable (World Bank, 2008). Godfray (2010) noted that more than one in seven people have limited access to food, and with the projected population increase, this number is likely to grow if measures are nottaken. In addition, FAO and the International Fund for Agricultural Development (IFAD) in 2009noted that more than a billion people were either malnourished or unable to meet their basic needs of food commodities (Godfrey, 2009). The increase in population could result in competitionfor shared resources such as land and water, consequently increasing food demand. The effect of climate change is projected to further heighten this demand (Royal Society of London, 2009). Projections show that a significant population that will be residing in the vulnerable countries by 2050, will likely face food insecurity (Lipper et al., 2014). For example, in countries such as Ghana, more than half of the population, directly and indirectly, relies on the agricultural sector, and with the projected change in climatic patterns, they are likely to face food insecurity (Mensah,2017). Climate change will jeopardize food security, especially as the smaller part of the agricultural area is under irrigation (Worqlul et al. 2019), leaving a more considerable part rainfall reliant.

On the other hand, climate change could have a positive effect on the productivity of crops. Ludwig and Asseng (2006); Jablonski et al., (2002) suggest that yields could improve because of the increased concentration of carbon dioxide in the atmosphere. This is through an elevated photosynthesis rate resulting in more energy and hence rapid plant development often referred to as the carbon-dioxide fertilization effect (Degener, 2015). It has been widely expected that C3-plants such as wheat, rice, and barley will benefit from increased carbon-dioxide concentrations because they rely on carbon-dioxide for their photosynthesis (Degener, 2015). Initially, rising temperatures can helpwinter grains and spring wheat; they will, however, inhibit an optimal development throughout theseasons. When compared, however, C4 plants such as maize and sorghum react differently to thechanges in carbon-dioxide because their rate of photosynthesis does not increase like that of C3- plants towards today's carbon dioxide concentration (Ehleringer and Cerling, 2002; Chmeilewski,2007; Lambers et al., 2008). Taylor et al., (2014) also note that, maize, the major staple cereal cropin southern Africa, is a C4 plant, which will benefit very little from increased carbon-dioxide concentrations. Furthermore, in countries like the USA, Europe, and others that lie in the middleand higher latitudes, climate change is expected to improve the conditions for crop growth by extending the length of the growing season and allowing early maturity (Elmassah and Omran, 2015).

2.2.1 Food security in Zimbabwe

Food insecurity is a challenge being faced by many African countries, including Zimbabwe. In Zimbabwe, agriculture accounted for about 18% of the country's GDP (GoZ, 2010). The frequency of droughts has affected the agricultural sector immensely, and yields have been declining. As mentioned earlier, periods of severe droughts have been observed in the years 1991–1992, 1994–1995, 2002–2003, 2015–2016, and 2018–2019 (Frischen et al., 2020), thereby affecting not only the country's economy but also the livelihood of a large populace. Zimbabwe's agricultural system comprises smallholder farmers, among others; they grow a significant amount of the maize in the country, and it is most likely to be affected by droughts (FAO, 2003). Smallholder farmers are vulnerable to climate change due to limited adaptive capacity because of poor living standards and heavy reliance on inefficient technologies (Mapfumo et al., 2010). Their vulnerability could expose the country to food insecurity.

The impact of climate change on food security has the country seeking out food handouts and other forms of foreign aid (Manyeruke, 2013). The Zimbabwe Nutrition Sentinel Site Surveillance System (2008) noted that about half of the Zimbabwean population had no food in 2008. The urban andrural dwellers faced food shortages, with the poor in the rural area mostly affected (FAO, 2008). In 2011 and 2012, the country had to import maize due to shortages caused by a reduction in rainfall amounts received (The Zimbabwean, 2012). Reliance on food importation has its effects on the country's development. Extreme weather events such as cyclones have hit the country for example, in 2000 and 2003, Cyclone Eline and Cyclone Japhet, respectively. These hydrological disasters have negatively impacted the agricultural sector (Manyeruke, 2013).

Zimbabwe has a dry period that extends up to seven months, and in recent years the country has been experiencing frequent droughts (Unganai, 2009), which could potentially result in food insecurity. Drought conditions brought by climate change are believed to be hindering the country from achieving some of the sustainable development goals (SDGs), including food security, good health, and well-being (Frischen et al., 2020). Mutekwa (2009) notes that the results of these droughts-like conditions could halve yields in Zimbabwe, that is, high temperatures and low rainfall projections. Reduced crop production, prevalent under extreme weather conditions such as droughts, reduces the available food commodities and is associated with higher prices, thereby exposing the poor to hunger and starvation (Chaves and Davies, 2010). Also, the changing climate can affect the production and access to food in many poverty-stricken regions of the world (Magrin and Gay Garcia, 2007). This information is pivotal in areas such as Sub-Sahara, where various countries, including Zimbabwe, are vulnerable and exposed to climate change (Madzwamuse, 2010). Tobacco as an important crop generates a significant amount of revenue through export earnings (GoZ, 2010), this revenue is directly used to import other food commodities into the country to ensure food security. Therefore, in the event that extreme climate conditions affect tobacco yields, revenues to import essential food commodities will consequently be negatively affected thus contributing to food insecurity.

Food insecurity in Zimbabwe has been on the rise at both national, regional, and household levels, and likely to intensify as the climate changes. At national and household levels, food security means one can afford or have the means to produce their own food, and this security has been affected by the economic environment in the country, with many people being poor and suffering from hunger. It is known that food insecurity directly translates to poverty, and this situation hinders development within the country (Manyeruke, 2013). The hunger situation is projected to escalate even further due to changes in rainfall patterns attributed to climate change.

Furthermore, the lack of a "comprehensive agricultural policy framework" has worsened the country's food insecurity situation. The existing agricultural policies have strategies meant to address food insecurity, for example, the Zimbabwe Agenda for Sustainable Socio-Economic Transformation (ZIMASSET) (Matutu, 2014); however, the economic and political environment in Zimbabwe deters the implementation of these strategies. For example, smallholder farmers in drier parts of the country, such as Mudzi district, which lies in Mashonaland East, are expected to be the worst affected by food insecurity induced by climate change in the absence of policies. (Mango, 2014). Efforts are being made to address the situation; the International Centre forTropical Agriculture (CIAT) is implementing projects meant to improve food security in the district of Mudzi (WFP, 2012). It is important to note that a need for the articulation of more comprehensive and extensive research is necessary to facilitate adequate adaptation.

Chapter 3: Material and Methods

This chapter outlines the study area, its geographical features, climatic conditions, the agricultural systems. Furthermore, the chapter also contains the climate data used, suitability modelling, as well as other materials and methods relevant to this study.

3.1 Study area

3.1.1. Geography and Climate

Zimbabwe a landlocked country in Southern Africa located between 15-22°S and 25°- 33°E and covering an area of 390 580 km^2 (Brown et al., 2012), was chosen as the study area. The country is bordered by South Africa, Botswana, Zambia, and Mozambique. It lies within the tropics, and the mean annual rainfall varies from 300mm in the Limpopo Valley up to3000mm in the eastern mountainous area (Mugandani et al, 2012). Zimbabwe has two main seasons: the dry, and the rainy seasons. The dry season extends from April to mid-October and the rainyseason extends from end-October to February-March (Brazier, 2017). Most of the countrycomprises Savanna grasslands (Buckle, 1996). The mean daily minimum and maximum temperatures have risen by approximately 0.2°C and 0.5°C per decade between 1962 and 2000 (Rurinda et al., 2014). The country is projected to witness further adverse effects of climate change(IPCC, 2014).

3.1.2. Agricultural sector

The agricultural sector plays a significant part in contributing 18% of the country's GDP and accounts for more than 50% of the raw materials supplied to the manufacturing industry (GoZ, 2010). Frequent droughts and dry spells affect the rainfed crops (Harrison etal., 2011; Mugiyo et al., 2018), and in general, the suitable areas for cultivating maize are expected to decrease by 2080. Zimbabwe is divided into five agro-ecological regions of different agricultural potential based on annual rainfall, temperatures received, soil properties, etc. (Vincent and Thomas, 1961). These zones shown in Figure 2 below, were used to discuss the results of this paper.

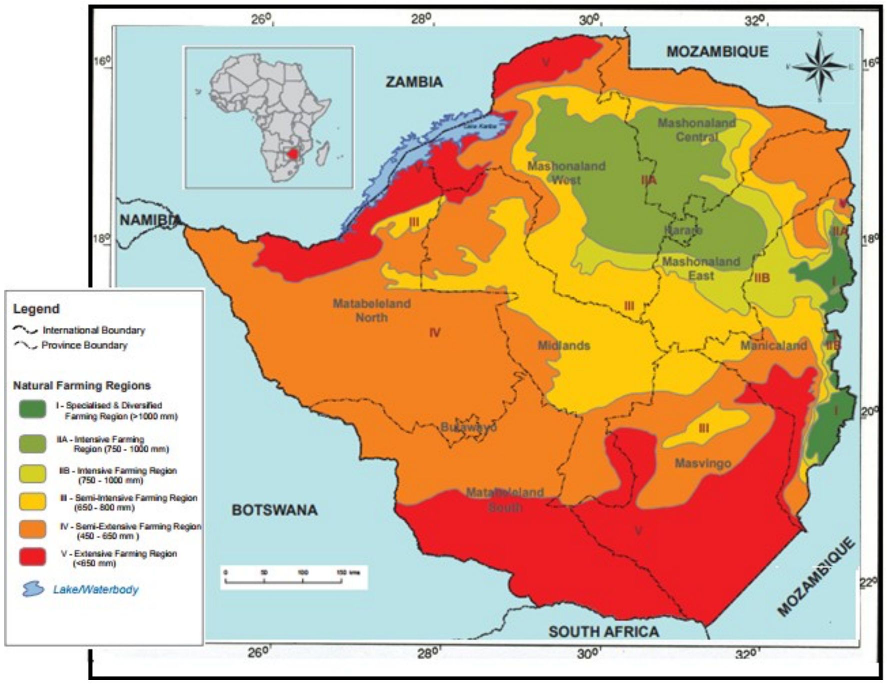


Figure 2. The location of the study area (Zimbabwe) showing agro-ecological regions (natural farming regions) and Provinces.

Source: Department of the Surveyor-General, Zimbabwe.

The economy and livelihoods of the population in Zimbabwe are heavily reliant on rainfed agriculture (Ayers et al., 2009). A significant percentage of the rural population in Zimbabwe relies upon rainfed agriculture, making them vulnerable to extreme weather events such as droughts (Mano and Nhemachena, 2007; Ministry of Environment, Water and Climate, 2015). Of all the crops grown, maize (*Zea mays L*) is one of the most important crops in Zimbabwe's agricultural system. It is a staple cereal crop, and thus it is vital for food security and people's livelihood (Basera, 2015). While Zimbabwe was once regarded as the breadbasket of Southern Africa, its crop production has been declining substantially (Mugiyo et al., 2021), and climate change and climate variability are factors that have led to this decline. An increase in temperatures and drought recurrence have beenwitnessed, and these conditions are affecting the suitability of the maize crop (Mugiyo et al. 2021).Therefore, analyzing the sensitivity of maize to rainfall and temperature variations is of direct value in maintaining and improving people's food security and livelihood.

On the other hand, tobacco (Nicotiana tabacum) is also rainfed, profitable, and important cash crop contributing to the country's economy, creating employment, and promoting livelihoods. Zimbabwe is the largest tobacco leaf producer in Africa, and the crop remains significant to the economy (Tobacco sales report, 2019). Its production was affected by the Land Reform Programme in the year 2000, among other factors; however, since 2010 its production has been recovering (Chingosho et al., 2021). Of the 10 provinces in Zimbabwe, Manicaland is the fourth-largest producer of leaf tobacco, after Mashonaland West, Mashonaland Central and Mashonaland East (Chingosho et al., 2021). Additionally, a study conducted by Chemura et al., (2013) showed that climate change would likely affect the suitability of tobacco in these provinces. Since the crop is rainfed, the effects of climate change, especially a decrease in rainfall patterns, will highly affect the climate suitable for its growth. Therefore, due to its economic value to the country and its vulnerability to climate change, it is pivotal to assess the crop's sensitivity to temperature and rainfall variations.

3.2 Climate and sensitivity analysis

To examine the effect of climate change on suitability, a sensitivity analysis can be performed (Boer et al., 2003; Thornton et al., 2009; Anderson et al., 2014). This sensitivity analysis can be aided by various parameters, for example, using historical climate data that can be manipulated to simulatesensitivity. This research used historical monthly weather data from the climate data portal, WorldClim, which was downscaled by the Climate Research Unit, using WorldClim 2.1 (Harris et al., 2014; Fick and Hijmans, 2017) for bias correction. Figure 3a and 3b below give an exampleof the WorldClim data: *a*- globally and *b*- on the area of study, Zimbabwe. WorldClim is a set of global layers depicting monthly climatology (minimum, average, maximum temperatures, and precipitation) (WorldClim data). The downloaded historical data set included the monthly averageminimum and average maximum temperatures (°C) and total precipitation (mm). The spatial resolution is 2.5 minutes (~21km^2).

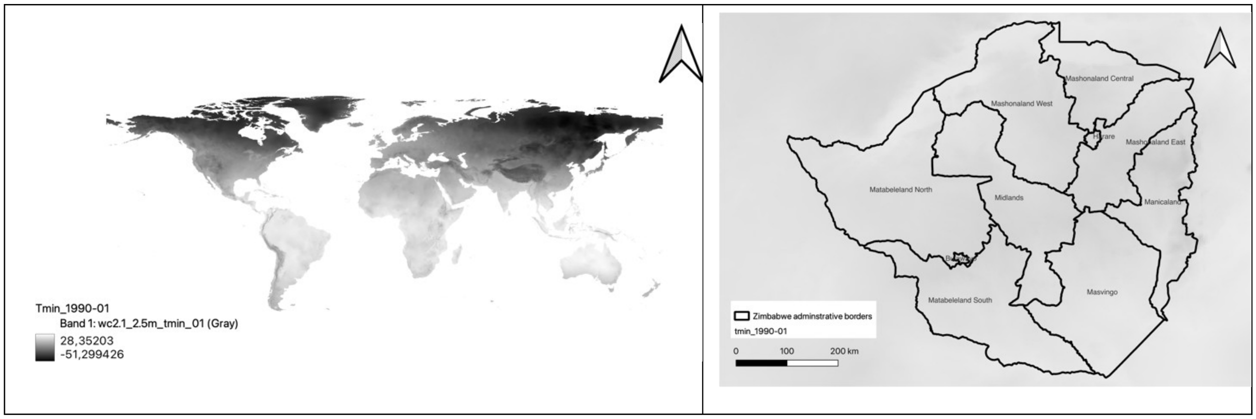


Figure 3 *a(left) and b (right). An example of the WorldClim data globally for minimum temperature for the month of January 1990 (b) and an extract of the area under study, Zimbabwe for the same period respectively.*

The assessment of climate suitability in Zimbabwe was carried out concentrating on historical climate data sets, recorded monthly for the period 1990-2018. This historical data was used as the baseline data for the study area. The climate data were downloaded, covering the entire world however, they were clipped to cover Zimbabwe using QGIS, version 3.18, which is a free and open-source desktop Geographic Information System application that allows for viewing, editing, and analyses of geospatial data as well as composing and exporting graphical maps and were converted into ASCII *(*asc)* format. These **asc* files were then imported into DIVA-GIS to create GRID (**grd*) files, supported by the application. The **grd* files were converted into climate **clm* files and processed with the Ecocrop model to simulate maize and tobacco suitability under the baseline data.

Temperature and rainfall are important climate variables used to determine the effects of climate change at various scales (Cong et al., 2012). The two climatic variables directly affect crop yield. Rainfall influences crop production as it influences photosynthesis and leaf area; on the other hand, temperatures affect the length of the growing season (Egbebiyi et al., 2019). The temperatures were projected to increase by a range of 2-4°C by 2021 (IPCC, 2013) thus, this research proceeded to assess spatial suitability using 2°C, 3°C, and 4°C as tested temperature level variations. Rainfall is projected to decrease (IPCC, 2013); however, projections retain more significant uncertainties, and this research used a +/-5%, +/-15%, and +/-30% annual average precipitation to carry out spatial suitability assessment. Sensitivity analysis was performed for the above-mentioned temperature levels (2°C, 3°C, and 4°C), for rainfall variations (5%, 15% and 30% increase and decrease), and a combination of both temperatures and rainfall variations. To determine the areas likely to change under the varying climate patterns, 3 temperature-only variants, 6 rainfall-only variants, and 18 combined temperature/rainfall variants were computed. The **grd* files were created by variation of the baseline data set and exported into DIVA-GIS for simulating the maize and tobacco suitability. Finally, QGIS was used to compute the maps of suitability difference from each variant to the baseline, to get a visual presentation for each data set, as shall be shown in chapter 4 below.

3.3 Modelling suitability

This research used a quantitative approach popular in the field of natural sciences. This technique employs mathematical models, statistics, modelling, and data analysis (Glesne, 2011). The term model, according to Dejenie (2019), refers to "*a schematic representation of the idea ofa system or an operation of imitation or a set of equations, in which it represents the overall behavior of a system.*". There are several suitability models, each possessing different assumptions and different uncertainties (Rivington and Koo, 2011). Some of these models includethe Maximum Entropy (MaxEnt) Model, Ecocrop, and the widely used 'The Decision Support System for Agrotechnology Transfer (DSSAT) (Thorp et al., 2008; Liu et al., 2011; Abera et al.,2018), and Aquacrop among others.

The MaxEnt model is popularly known for its predictive accuracy and is also easy to use (Phillips et al., 2006; Maguranyanga and Murwira, 2014). This model has been used to project the impact of climate change on the distribution of crops (Kogo et al., 2019) and to study climate suitability for maize cultivation (He and Zhou., 2012), among others. Meanwhile, DSSAT is a model developed to simulate plant growth, development, and crop yields in a uniform area (Jones et al., 2003). The inputs required in this model include soil conditions, weather, and management practices such as irrigation (Wu et al., 2013). Another model used in simulating crop growth is the Aquacrop modeldeveloped by FAO's Land and Water Division (FAO, 2021). It simulates crop yields and is moresuited to conditions where water is the major limitation of crop production.

This study will not use process-based models (e.g., DSSAT, AquaCrop) because they are data demanding and with high computation demand. We preferred an empirical approach, using the

Ecocrop model, allowing for large spatial representation to analyze climate suitability. Suitability indices, found in the Ecocrop model, have been used to assess a variable's response to a set of environmental factors (Lane and Jarvis, 2007). These indices have been developed to quantify the relationship between climate and crop performance in the unavailability of detailed information (Eitzinger et al., 2009). The Ecocrop model has been used in several studies for example, Lane and Jarvis (2007); Ramirez-Villegas et al., (2013); Ezekannagha and Crespo (2019), Egbebiyi et al., (2020), to determine the suitability of crops in response toclimate.

3.3.1 Ecocrop Model

The Ecocrop model was designed with crop environmental requirements information. The FAO-Ecocrop Database (FAO, 2000) comprises more than a thousand different crops' parameterizations. Although the parameterizations in this database have not been validated the extensive literature or expertise informing those parameters offers, at such a large scale, a useful/valid estimate of the crop's suitability under historical climate and its variants (Yadav et al., 2011). The model allows for assessing the impacts of climate change on several crops through the spatial analysis of regions affected by climate change (Lane et al., 2007). It assesses the suitability of a crop over a large geographic extent rather than a field point or accumulation of field points in response to; monthly rainfall totals (mm), monthly minimum average, and mean temperatures over the length of its growing season, thereby producing a suitability index score from zero (not suitable) to one (highly suitable), (Hijmans et al., 2001; Läderach, 2013).

When the conditions over the growing season are beyond the absolute thresholds (white area, see Figure 4a), the suitability index is zero (not suitable), a state where the crop cannot grow under average conditions. When the conditions are between absolute and optimum thresholds (a dark grey area, see Figure 4a), it shows a state where the crop can grow under a low range of suitable conditions. Furthermore, when they are within the optimum threshold with a suitability index of 1 (a light grey area, see Figure 4a), it indicates a state where the crop can grow optimally under a high range of suitable conditions

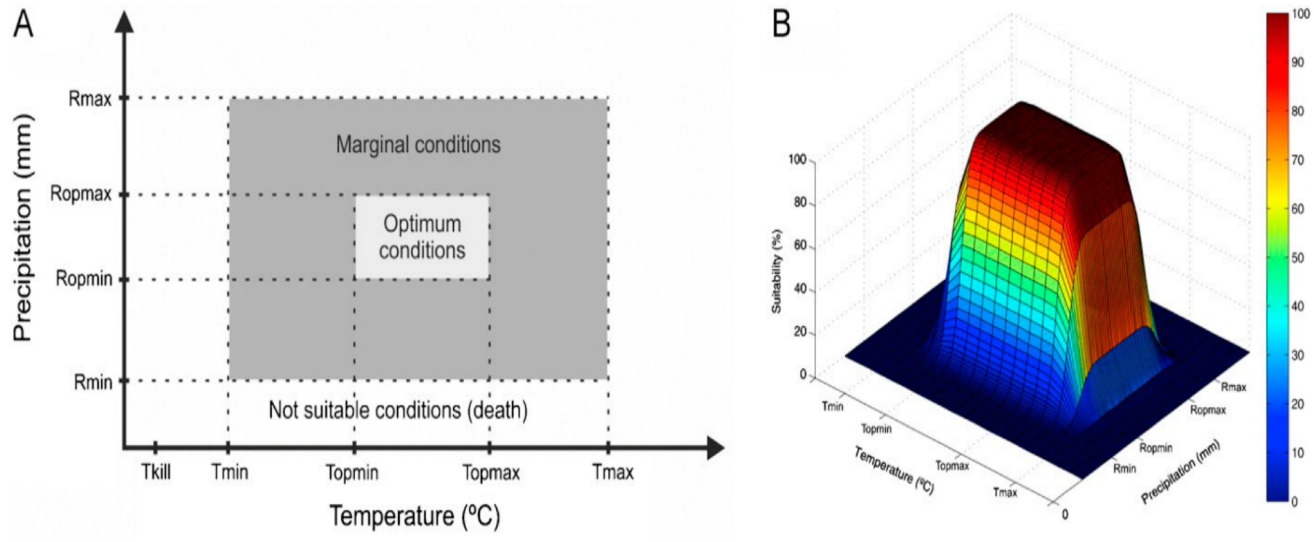


Figure 4. (a) Two-dimensional and (b) Three-dimensional diagram of the Ecocrop model showing climate thresholds and crop suitability classification. Source: Ramirez-Villegas et al. (2013).

It is important to note that this study did not carry out further ground-truthing or calibration of climate parameters for both crops under study because it is accepted that no cell singled out would be accurate, but the agglomeration of suitability computed over large spatial areas and a large temporal duration characterizes well enough the long-term suitability analyzed here. The major advantages of using the Ecocrop model are that it is transparent, easy to apply, and the amount of data needed is limited (Ramirez-Villegas et al., 2013; Myeni et al., 2019). Apart from its simplicity, the results produced by the Ecocrop model can be used to understand the likely impacts of climate change on the crop's suitability under study. We are further comforted that its results have been found to agree with the results computed using other more complex crop models (Ramirez-Villegas et al., 2013).

3.3.2 DIVA-GIS

The Ecocrop model is embedded in the Geographic Information System software called DIVA-GIS (Hijmans et al., 2005). This is a User Interfaced program for mapping and analyzing spatial data with more emphasis on analyzing the distribution of organisms in geographical areas and under different ecological patterns (Hijmans et al., 2005). It uses climate data from the WorldClim database (WorldClim, 2011) and computes the suitability index score described above. The model manual (Hijamans et al, 2005) notes that the suitability of temperature is computed by comparing the crop parameters with the minimum and mean temperature, whereas the rainfall suitability computation is carried out using the total rainfallrequired during the growing season.

DIVA-GIS version 7.5 (Hijmans et al., 2012) was used to implement the Ecocrop model and to generate the maps of suitable areas. Ecocrop is embedded in DIVA-GIS and has been interfaced with monthly precipitation and temperature data to enable suitability mapping of a geographical area to promote the growth of certain crop species based solely on climate variables. Ecocrop performs calculations using the two climate variables (temperature and rainfall) to determine the suitability of a crop based on the growing seasons of the year. The Ecocrop in DIVA-GIS shows the ecological thresholds which determines suitability, *see* Figure 5below, and these vary from crop to crop.

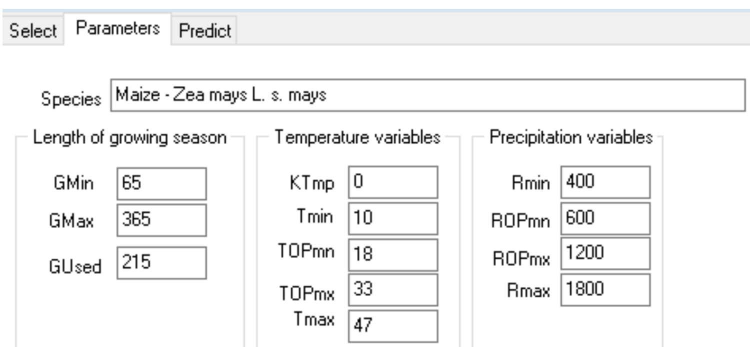


Figure 5. Ecocrop parameters interfaced in DIVA-GIS for maize (*Zea mays L.*)

In Ecocrop interfaced in DIVA-GIS, the growing period is defined in days between Gmin (start of growth) and Gmax (end of growth), see Figure 5 above. According to the DIVA-GIS manual (Hijmans et al, 2012), to determine the thresholds of a growing season for a certaincrop, certain temperature parameters are used. These include: KTmp (the absolute temperature that will kill the plant), Tmin (the minimum average temperature at which the plant will grow), Topmn (the minimum average temperature at which the plant will grow optimally), Topmx (the maximum average temperature at which the plant will grow optimally), Tmax (the maximum average temperature at which the plant will cease to grow), (Hijamans et al., 2012).

3.3.3. Baseline

The Baseline is defined as a starting point used for comparisons (Cambridge Dictionary). This research uses the historical climate data for the past 29 years (1990-2018) as the 'baseline' to perform a spatial analysis of suitability resulting from increased average temperature levels of 2°C, 3°C, and 4°C; from decreased and increased average rainfall levels by 5%, 15% and 30%; and from the combined variation of temperatures and rainfall.

Figures 6 and 7 show the suitability maps in panels for the historical climate suitability dataset for the period 1990-2018, for maize and tobacco respectively, in the case of Zimbabwe. The suitability indices shown in DIVA-GIS include "excellent", "very suitable", "suitable", "marginal", "very marginal" and "unsuited", respectively in color "red", color "orange", color "yellow", color "light green", color dark green" and color "grey", see Table 1 below. The frequency occurrence over the plotted map of these 6 levels is shown in histograms for maize and tobacco in panels *b (right)*, in Figures 6b and 7b respectively.

Table 1. Defining suitability indices as shown in DIVA-GIS

Grey	Not suitable
Dark green	Very Marginally
Light green	Marginal
Yellow	Suitable
Orange	Very Suitable
Red	Excellent

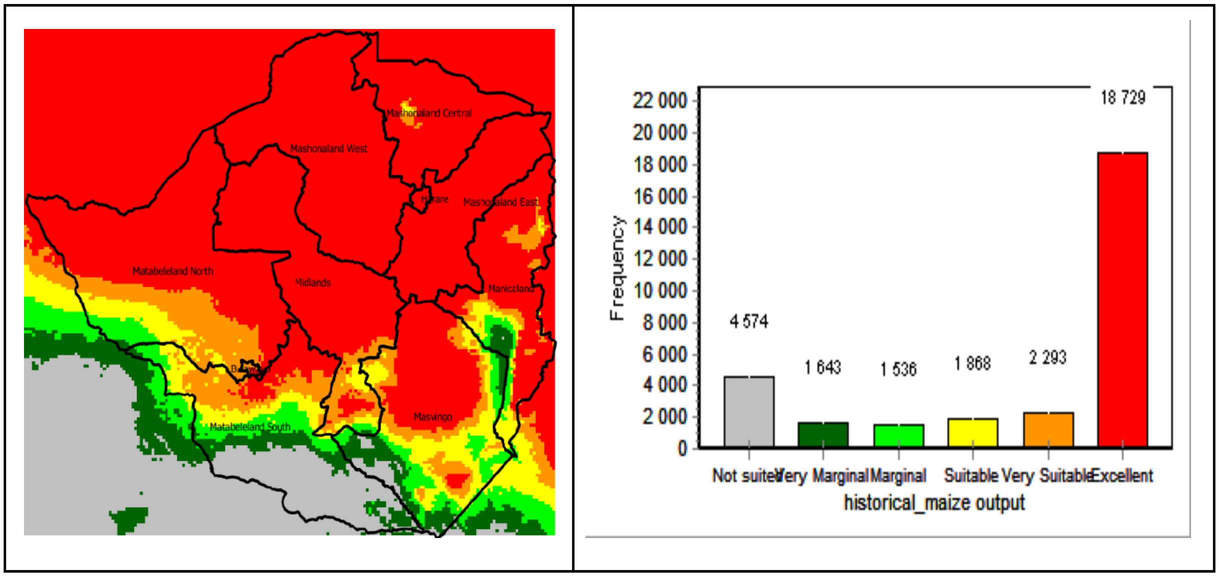


Figure 6. a (left) Historical climate suitability for the maize crop from 1990-2018. b(right) histogram representing the frequencies of climate suitability for maize from 1990-2018.

The maps (Figures 6a above and 7a below) indicate a pattern in the southern part of the country. For both maize and tobacco, there is a **belt** which extends from the western part to the south-eastern part of the country. This **belt** separates the excellent regions in the north from the unsuitable regions, in the south and this **belt** consists in a gradual decrease from excellent, very suitable, suitable, marginal, very marginal to not suited. This **belt** shall be used to observe and discuss the pattern of change resulting from temperature and precipitation variations.

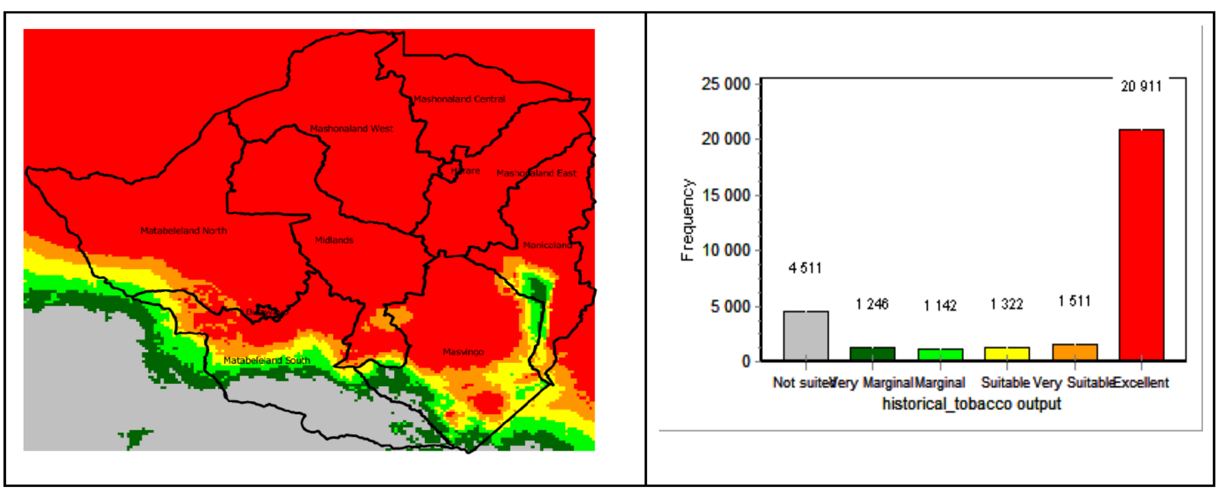


Figure 7. a(left) Historical climate suitability for the tobacco crop from 1990-2018. b(right) histogram representing the frequencies of climate suitability for tobacco from 1990-2018.

3.4. Model's simulations and ground-based evidence

It is important to note that the Ecocrop model simulated suitability for the whole country based on crop and climate parameters, that is, precipitation, and temperature. The model did not consider other variables such as soils, land use, etc. Zimbabwe is divided into five agricultural regions, known as natural ecological regions (see Figure 2 in Chapter 3), based on several attributes that include rainfall, vegetation, and soil quality, among other factors. Moyo (2000) and Chingosho (2021) note that land quality declines as one moves from region one (I) to five (V). Of these five natural regions,only the first three (region I, II, and III) are suitable for maize cultivation, and one (region II) is suitable for tobacco farming. Natural Region I receives annual rainfall amounts greater than 1000mm, and it covers parts of Manicaland Province and is suitable for dairy farming, forestry, coffee, and maize production, among others. Natural Region II receives annual rainfall ranging between 750-1000mm in the provinces of Harare, Manicaland, Mashonaland West, Mashonaland East, and Mashonaland Central and the region is suitable for intensive farming based on maize, tobacco, cotton, and livestock (Chingosho et al., 2021).

Tobacco is farmed in high potential agro-ecological regions, generally receiving reliable rainfall ranging between 750-1000mm, which is ideally suitable for its intensive farming (GoZ, 2012). For example, more specific areas include Mt Darwin, a district in the Mashonaland Central province that accounts for approximately 30% of the country's tobacco output (TIMB, 2019). Nyazura district of Manicaland Province, both west and east, is said to be one of the largest producing areas of tobacco in Zimbabwe (Nyambara and Nyandoro, 2019; Chingosho, 2021), among other areas. Its production surpasses other districts in the country. Lastly, Region II receives rainfall ranging between 680- 800mm, covering parts of Manicaland, Midlands, Masvingo, and parts of Mashonaland West and East.This Region experiences periodic droughts, unreliable start of the rain season, and maize cultivation is marginal. Regions IV and V have an annual rainfall of below 600mm and are very marginal for maize cultivation (MAMID, 2013). Therefore, the results of this research shall be discussed based on the regions known to be suitable for cultivating the crops under study on the ground.

3.5. Summary

Table 2. Summary of materials and methods ***in relation to the study's objectives***

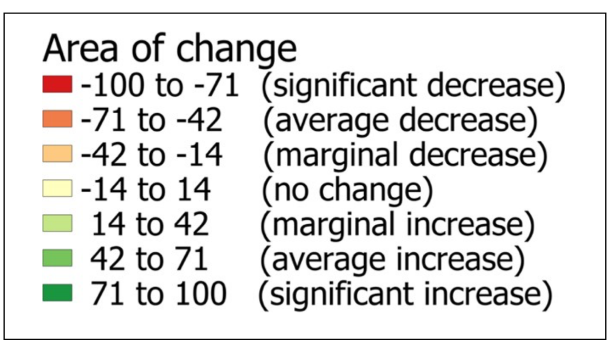
Objective	**Material and Methods**
1. To investigate the spatial suitability of maize and tobacco under historical average conditions in Zimbabwe	The 1990-2018 historical data set was used. Analysis was performed using QGIS, Ecocrop: for the crops (maize and tobacco) and DIVA-GIS. (Figures 6 and 7 above)
2. To perform a spatial analysis of suitability resulting from increased average temperature levels by 2°C, 3°C and 4°C	The historical climate suitability for both maize and tobacco was used as the baseline to perform the spatial analysis resulting from increased average temperature.
3. To perform a spatial analysis of suitability resulting from decreased and increased average rainfall levels of 5%, 15% and 30%	The historical climate suitability for both maize and tobacco was used as the comparison baseline for the suitability resulting from increased and decreased average rainfall levels.
4. To spatially analyze the crops sensitivity to the combined variation of temperature and rainfall.	The historical climate suitability for both maize and tobacco was used as the baseline to perform the spatial analysis resulting from the combined rainfall and temperature variation.

Chapter Four: Results

This chapter presents the results obtained from simulating, and analysis of baseline data compared to its variants based on temperature +2°C, +3°C and +4 °C and rainfall +/-5%, 15%, and 30% changes. The results show the first baseline compared to temperature-only variations where historical precipitation remains constant, second precipitation-only variations where historical temperaturesremain constant, and lastly, a combination of temperature and precipitation variations as summarized in the Table 3. Also, *Insert 1* below shows the legend applied across all the following maps showingthe areas experiencing change under the varying temperatures.

Table 3. Structure of results

		Precipitation changes						
		-5%	-30 %	-15%	Historical	5%	15%	30%
temperatur echanges	historical	Result section 4.2			historical baseline in Materials and Methods	Result section 4.2		
	2°C	Results section 4.3			Result section 4.1	Results section 4.3		
	3°C							
	4°C							



Insert 1. Legend applied to the maps showing the areas projected to change under the varying temperatures.

4.1 Temperature suitability

4.1.1 Climate suitability analysis resulting from temperature increase by 2.0 °C.

4.1.1.1 Maize

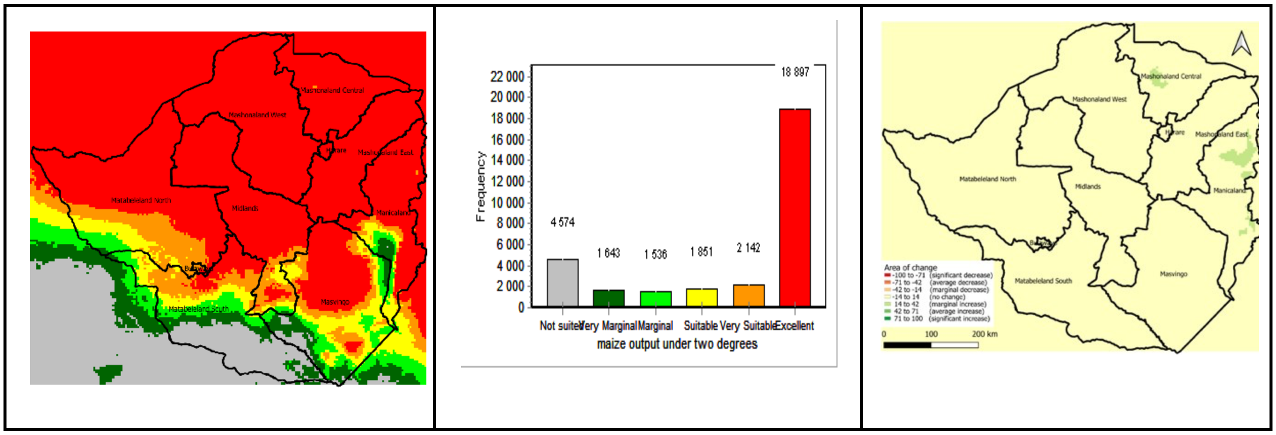


Figure 8 (left to right respectively). (a) shows the climate suitability for maize under a 2°C increased temperature. (b) histogram representing the frequencies and distribution of climate suitability for maize if temperatures increase by 2°C. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate (legend, see Insert 1 above).

A 2°C increase in temperature was simulated (assuming historical precipitation remains fixed), as seen in Figures 8a and b. Figure 8a above shows the climate suitability of maize, and Figure 8b shows a histogram (interpreting the map in Figure 8a) depicting the distribution of suitability scores. The above simulation shows that the climate suitability for maize in the country under 2°C temperature warming will be largely excellent, covering provinces including Harare, Mashonaland West, Mashonaland Central, Mashonaland East, most of Midlands and Manicaland, some parts of Masvingo and Matabeleland North. The frequency of this distribution, as shown in Figure 8b above is slightly higher (18 897) when compared to the historical "excellent" distribution in Figure 6b (18 729). Figure 8c shows the areas that will experience change under a 2°C temperature increase when compared to the historical baseline data. Provinces such as Matabeleland South will remain largely unsuited for the cultivation of maize and small parts of Masvingo province. For Matabeleland North and South, almost half of the area will change from very suitable to marginal; the same applies for Masvingo in the northern parts. Small parts of Manicaland province will range from being very suitable to very marginal. This distribution is consistent with the historical patterns, and the **belt** remains in the same pattern extending from the west to the south-eastern part of the country.

4.1.1.2 Tobacco

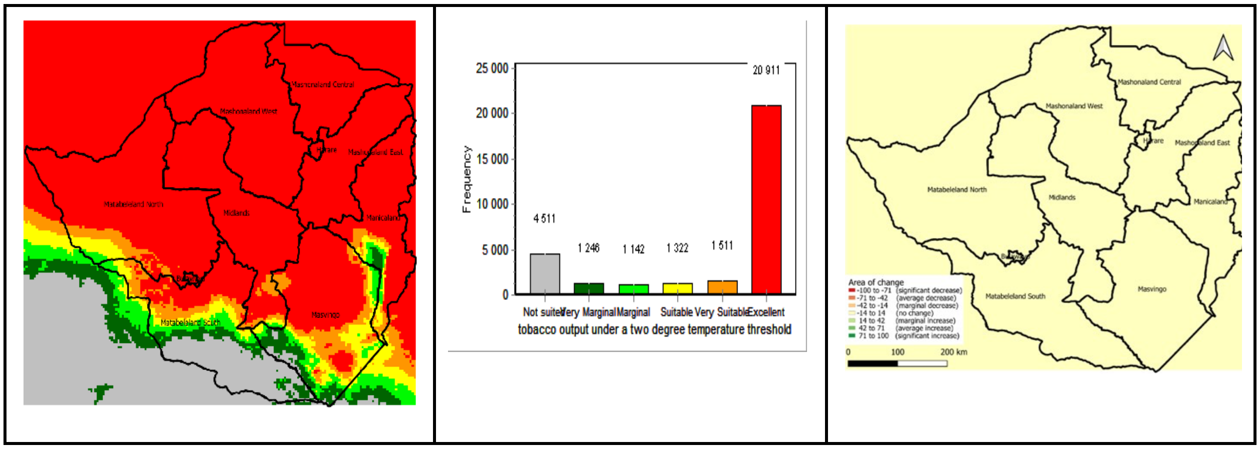


Figure 9 (left to right respectively). (a) shows the climate suitability for tobacco under a temperature increase of 2.0 ^{o}C. (b) histogram representing the frequencies and distribution of climate suitability for tobacco if temperatures increase by 2.0^{o}C. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

For tobacco (Figure 9a), the climate suitability under a temperature increase of 2^{o}C also shows to be excellent in large parts of the country; that is Mashonaland West, Central and East, Harare, Bulawayo, large parts of Matebeleland North, Masvingo and Manicaland provinces. A small part of Matabeleland North and South provinces will range from very suitable to marginal. Almost half of Masvingoprovince will be ranging from being very suitable to not suited. A large portion of Matabeleland South will remain unsuitable for tobacco cultivation compared with the historical output. The tobacco output under a 2^{o}C temperature increase, will likely be consistent with those under historical output as shown in Figure 9c. Figure 9c, shows that there is no noticeable difference between the historical climate suitability and the climate suitability under a 2^{o}C temperature increase for tobacco.

4.1.2 Climate suitability analysis resulting from temperature increase by 3°C.

4.1.2.1 Maize

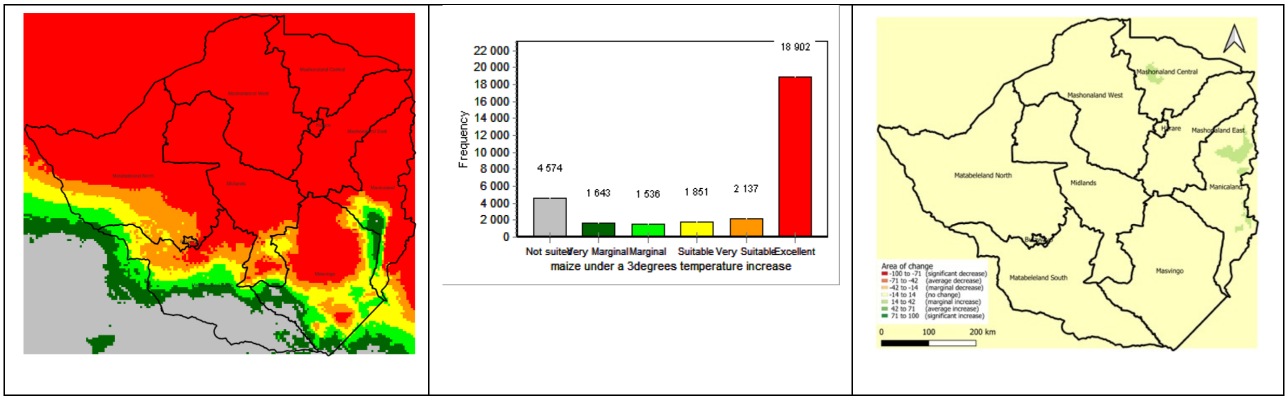


Figure 10 (left to right respectively). (a) shows the climate suitability for maize under a 3°C increased temperature. (b) histogram representing the frequencies and distribution of climate suitability for maize if temperatures increase by 3°C. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

A 3°C increase in temperature was simulated (assuming historical precipitation remains fixed), as seen in Figures 10a and b. Figure 10a above shows the climate suitability of maize, and Figure 10b is a histogram depicting the distribution of suitability scores. The above simulation shows that the climate suitability for maize in the country under +3°C temperature warming will be largely excellent, covering provinces including Harare, Mashonaland West, Mashonaland Central, Mashonaland East, most of Midlands and Manicaland, some parts of Masvingo and Matabeleland North. The frequency of this distribution, as shown in diagram 10b above, is slightly increased (18 902) when compared to the historical "excellent" distribution in Figure 6b (18 792). Figure 10c shows the areasthat will experience change under a 3°C temperature increase when compared to the historical baseline data. Provinces such as Matabeleland South will remain largely unsuited for the cultivation of maize and small parts of Masvingo province. For Matabeleland North and South, almost half of the area will range from very suitable to marginal; the same applies for Masvingo in its northern parts. Small parts of Manicaland will range from being very suitable to very marginal. This distribution is consistent with the historical patterns, and the **belt** remains in the same pattern extending from the west to the south-eastern part of the country.

4.1.2.2 Tobacco

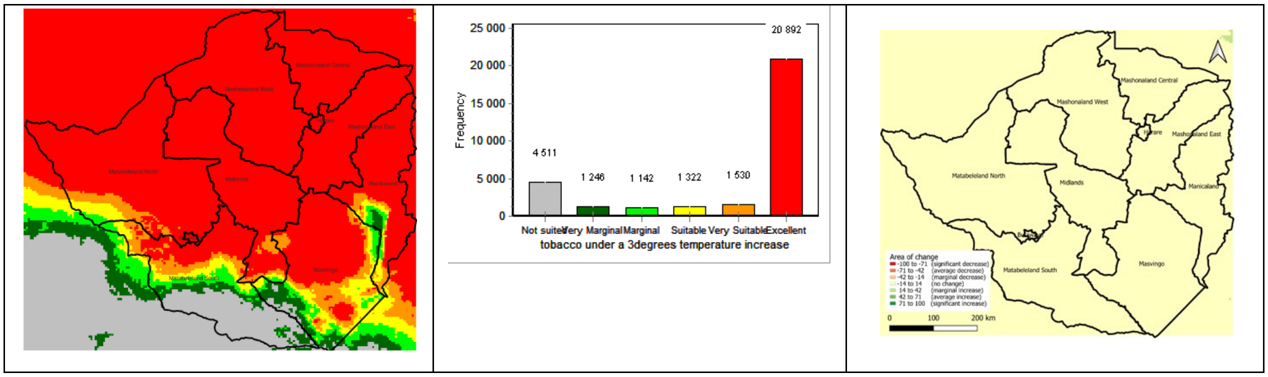


Figure 11 (left to right respectively). (a) shows the climate suitability for tobacco under a temperature increase of 3.0 °C. (b) histogram representing the frequencies and distribution of climate suitability for tobacco if temperatures increase by 3.0°C. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 11a shows that for tobacco, the climate suitability will likely remain excellent in large parts of the country; that is Mashonaland West, Central and East, Harare, Bulawayo, large parts of Matebeleland North, Masvingo and Manicaland under a temperature increase of 3°C. A small part of Matabeleland North and South will range from very suitable to marginal. Almost half of Masvingo province will be ranging from being very suitable to not suited. A large portion of Matabeleland South will remain unsuitable for tobacco cultivation compared with the historical output. The tobacco output under a 3°C temperature increase, will likely be consistent with those under historical output as shown in Figure 11c. The map in Figure 11c, shows that there is no noticeable difference between the historical climate suitability and the climate suitability under a 3°C temperature increase.

4.1.3 Climate suitability analysis resulting from temperature increase by 4°C.

4.1.3.1 Maize

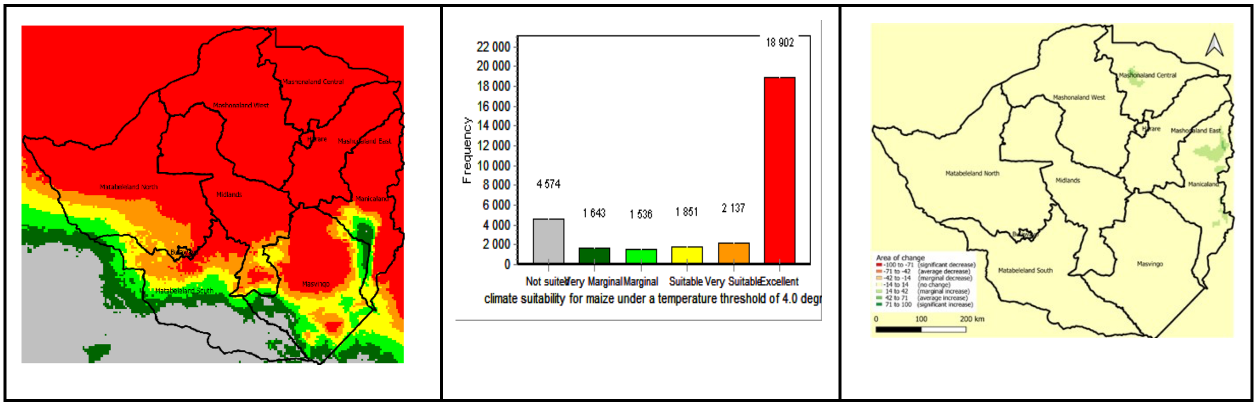


Figure 12 (left to right respectively). (a)shows the climate suitability for maize at a 4 °C temperature increase. (b) histogram representing the frequencies and distribution of climate suitability for maize if temperatures increase by 4°C. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Under a temperature increase of 4°C with historical precipitation data remaining fixed, Figure 12a above shows the climate suitability for maize. The above simulation shows that the climate suitability for maize in the country under a 4°C temperature increase will be largely excellent, covering provinces including Harare, Mashonaland West, Mashonaland Central, Mashonaland East, most of Midlands and Manicaland, some parts of Masvingo and Matabeleland North. The frequency shown by the histogram in Figure 12b indicates an increase (18 902) in “excellent areas” when compared to the historical distribution (18 729). Figure 12c shows these areas of increase that is Manicalandand Mashonaland Central. However, provinces such as Matabeleland South will remain largely unsuited for the cultivation of maize, as well as small parts of Masvingo province. Small parts of Manicaland will range from being very suitable to very marginal. Figure 12c shows the areas that are subject to change under a 4°C temperature increase, and these areas include Mashonaland Central and Manicaland Provinces.

4.1.3.2 Tobacco

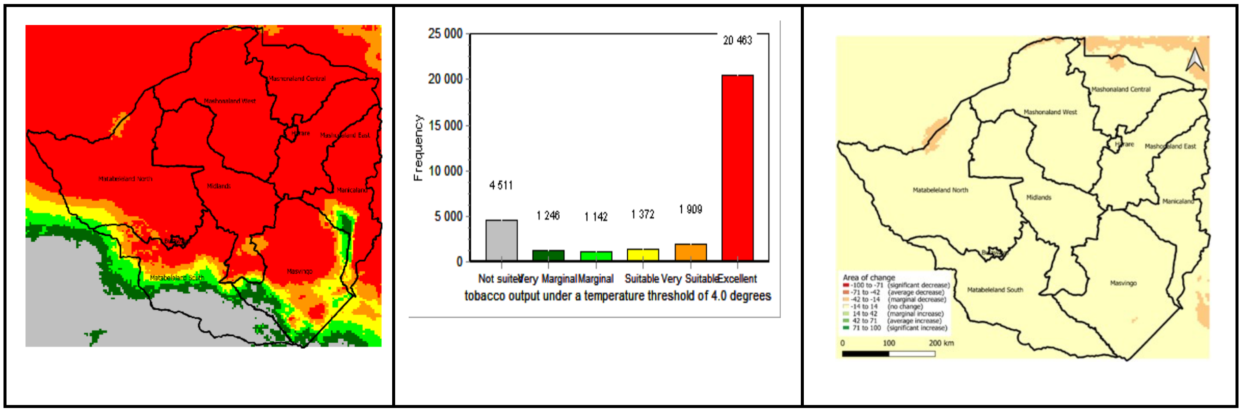


Figure 13 (left to right respectively) shows the climate suitability for tobacco under a 4°C temperature increase. (b) histogram representing the frequencies and distribution of climate suitability for tobacco if temperatures increase by 4°C. (c) shows areas of change when compared to the historical output.

For tobacco, Figure 13a, the climate suitability also shows to be excellent in large parts of the country; that is Mashonaland West, Central and East, Harare, Bulawayo, large parts of Matebeleland North, Masvingo and Manicaland. However, the frequencies of areas that will be excellent for tobacco in Figure 13b show a decrease when compared to that of the historical climate suitability for tobacco from 20 911 to 20 463. The **belt** follows the historical pattern, the pocketsof very suitable, suitable, marginal, and very marginal do not change when compared to that of the historical output. A large portion of Matabeleland South province will remain unsuitable for tobacco cultivation which is consistent with the historical output in Figure 7b. The map in Figure 13c showsthe areas that are projected to experience a marginal decrease when compared to the historical output, that is, within Masvingo and the northern part of Mashonaland Central Province, these provinces will experience a slight decrease in terms of climate suitability.

4.2 Precipitation suitability

4.2.1 Spatial analysis of suitability resulting from 5%, 15% and 30% decrease in the average precipitation.

4.2.1.1 Maize

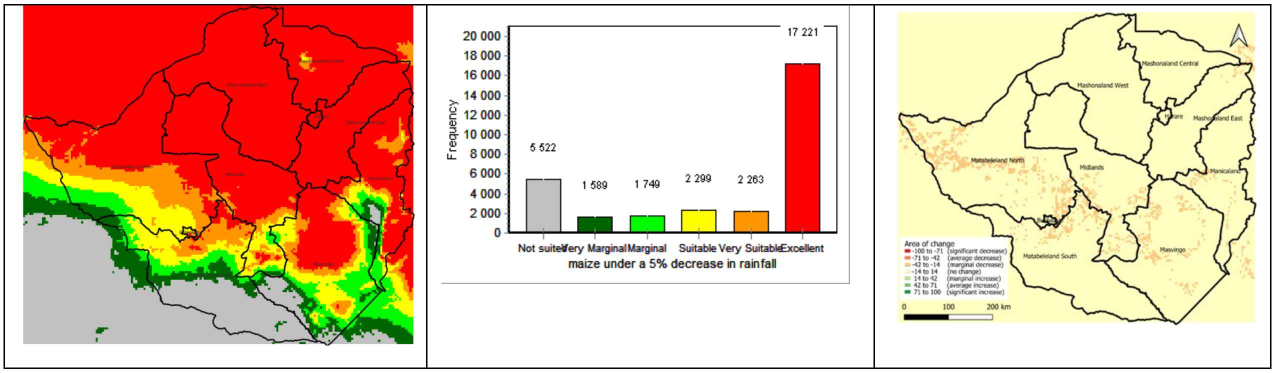


Figure 14 (left to right respectively). (a)shows the climate suitability for maize if precipitation decreases by 5%. (b) histogram representing the frequencies and distribution of climate suitability for maize if precipitation decreases by 5%. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Furthermore, suppose rainfall decreases by 5% of the average historical totals, assuming temperatures remain fixed, in that case, such climatic conditions indicate a marginal decrease in the areas suitable for the cultivation of maize as shown in Figures 14a, b. The **belt** in Figure 14a when compared with to the historical baseline shows a slightly different pattern. The **belt** expands moving northwards intothe areas that were historically excellent in terms of suitability and the pockets within the **belt** slightly increase in size moving northwards, especially the marginal, suitable, and very suitable pockets. When compared to the historical climate suitability patterns (18 729), the diagram above, Figure 14a shows a slight decline (17 221) in the areas suitable for the growth of rainfed maize. The extent of unsuitability indicates a marginal increase in Figure 14a covering most parts Matebeleland Southextending in Masvingo and small parts of Manicaland and Matabeleland North provinces and using frequencies shown on the histogram, Figure 14b, the unsuitable areas increase. Figure 14c showsthe areas that will experience change under a 5% decrease in precipitation when compared with that of the historical patterns. The map shows that parts of Matabeleland North extending into Matebeleland South, Bulawayo, parts of Midlands, Masvingo and Manicaland will experience a very marginal decrease in suitability.

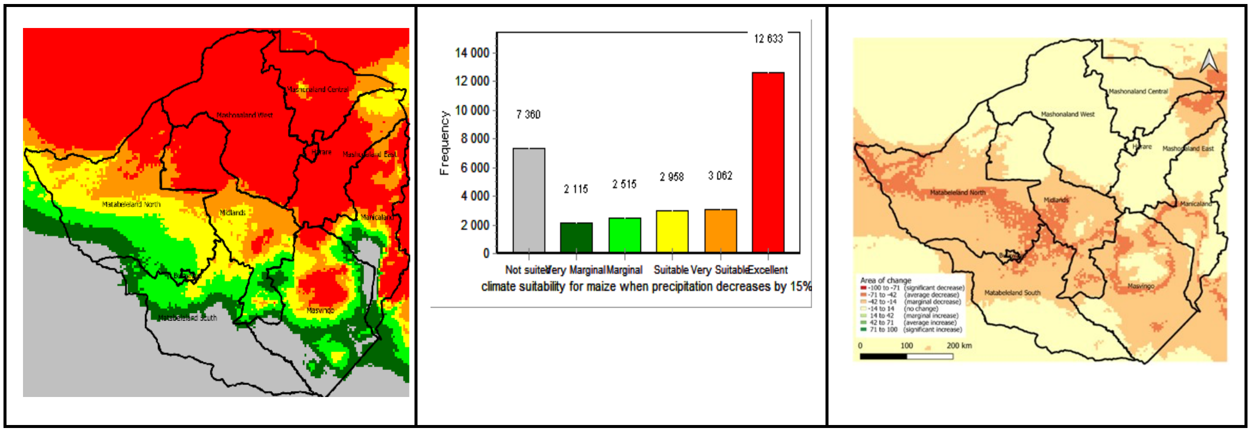


Figure 15 (left to right respectively). (a)shows the climate suitability for maize if precipitation decreases by 15%. (b) histogram representing the frequencies and distribution of climate suitability for maize if precipitation decreases by 15%. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Changes in precipitation by a 15% decrease on the average historical totals and fixed historical temperatures indicate a decline in the climate suitability pattern and distribution for maize cultivation as shown in Figures 15a, b. The **belt** on Figure 15a when compared with to the historical baseline shows a different pattern. The **belt** expands moving northwards into the areas that were historically excellent in terms of suitability. When compared to the historical climate suitability patterns (18 728), the diagram above, Figure 15a shows a considerable decline in the areas suitable for the growth of rainfed maize (12 633). The extent of unsuitability indicates an increase in Figure 15a covering large parts of Matebeleland South province extending into Masvingo province and small parts of Manicaland and Matabeleland North provinces and using frequencies shown on the histogram Figure 15b, the unsuitableareas increase. Areas that had climate suitable for maize during the period 1990-2018 when exposed to a 15% decrease in precipitation indicate a decrease as shown in on Figure 15b. These areas will decrease in terms of frequency (see figure 15b) which could have serious implications on the food security of the country. Figure 15c (using *Insert 1* above as the legend), shows the areas that will experience change under a 15% decrease in precipitation when compared with that of the historical data. The map shows that large parts of Matabeleland North extending into Matebeleland South, Bulawayo, parts of Midlands, Masvingo and Manicaland provinces will experience a marginal to an average decrease in suitability.

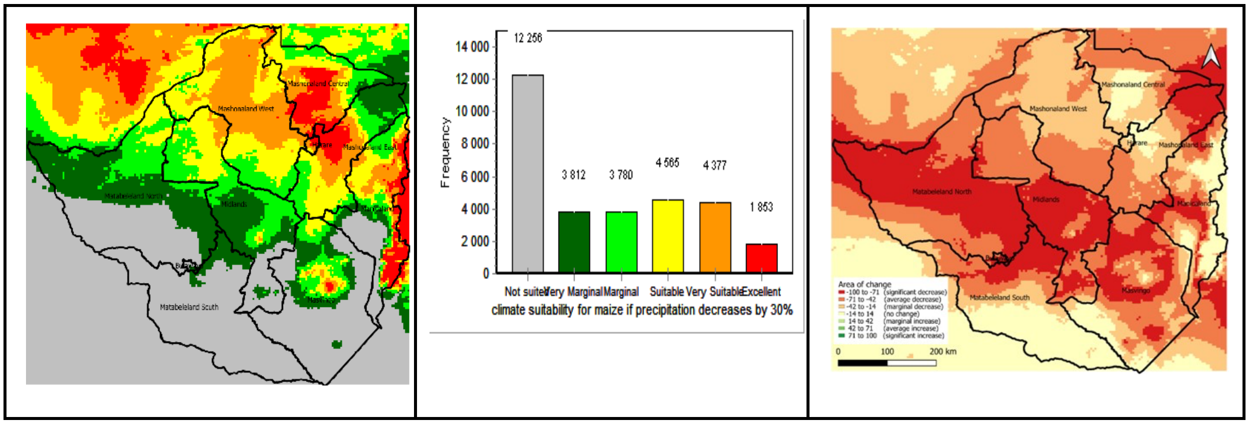


Figure 16 (left to right respectively). (a)shows the climate suitability for maize if precipitation decreases by 30%. (b) histogram representing the frequencies and distribution of climate suitability for maize if precipitation decreases by 30%(c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Changes in precipitation by a 30% decrease on the average historical totals accompanied by fixed historical temperatures indicate a significant decline in the climate suitability pattern and distribution for maize, as presented in Figures 16a, b. When compared to the historical climate suitability patterns (18 729, in Figure 6b), the diagram (Figure 16a) shows a significant decrease (1853 in frequency) in suitable areas for thegrowth of rainfed maize. Excellent areas will become very marginal to unsuited. The unsuitable area will expand northwards in Figure 16a, covering large parts of Matabeleland North and Southextending in Masvingo and small parts of Manicaland and Midlands. These areas that will undergochanges are represented on the map in Figure 16c. Areas with suitable climate for maize during the period 1990-2018, when exposed to a 30% decrease in precipitation, indicate a decrease in suitability, pushing the **belt** north-east as shown in Figure 16c. The suitable areas occur with a lower frequency which could likely impose serious implications on the country’s staple crop. Thepattern of the **belt** in Figure 16a, when compared to the historical baseline, shows a significant difference, the size of the **belt** increase in width moving northwards into the once suitable provinces. Figure 16c shows that these areas will experience a range of marginal, average, and significant decreases in suitability if precipitation decreases by 30%.

4.2.1.2 Tobacco

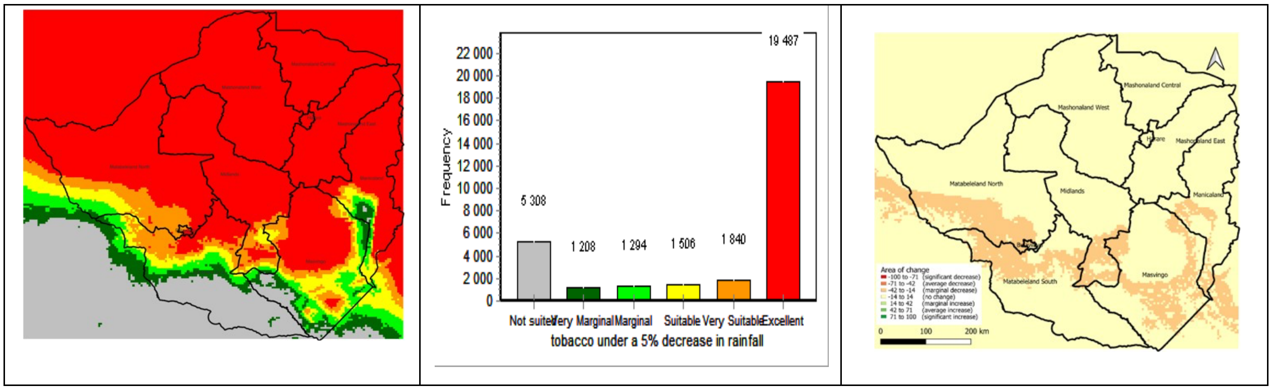


Figure 17 (left to right respectively) shows the climate suitability for tobacco when rainfall decreases by 5% of the historical data (b) histogram representing the frequencies and distribution of climate suitability for tobacco if rainfall decreases by 5% (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

According to Figure 17a above, if rainfall decreases by 5% of the historical average totals combined with historical temperatures, there will be a marginal decline in the areas suitable for tobacco cultivation. When compared to the historical climate suitability patterns, Figure 17a shows a marginal decrease, in the areas suitable for the growth of rainfed tobacco. Areas that had climate suitable for tobacco during the period 1990-2018, when exposed to a 5% decrease in precipitation indicate a decrease from being excellent into marginal, very marginal, and unsuitable as shown in Figure 17b, these areas will decrease in frequency, from 20 911 (Figure 7b) to 19 487, see Figure 17b. The extent of suitability indicates a marginal decrease in Figure 17a as the **belt** moves northwards covering large parts of Matebeleland South extending in Masvingo and small parts of Manicaland and Matabeleland North and using frequencies shown on the histograms, Figure 17b, the unsuitable areas also increase. Figure 17c shows the areas which are likely to experience a marginal decrease in suitability and these will include Matebeleland North, Matabeleland South, Bulawayo, part of Midlands, Masvingo and Manicaland Provinces.

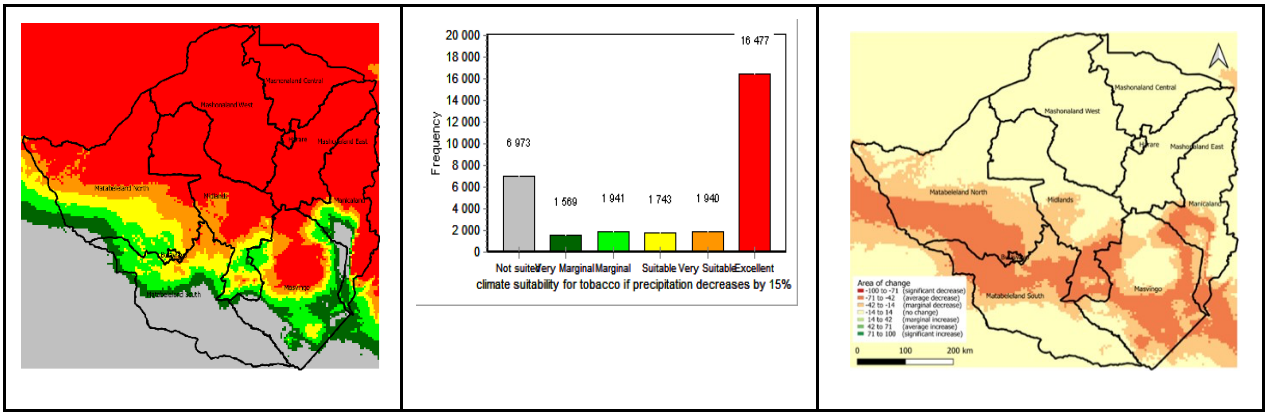


Figure 18 (left to right respectively) shows the climate suitability for tobacco when rainfall decreases by 15% of the historical data(b) histogram representing the frequencies and distribution of climate suitability for tobacco if rainfall decreases by 15% (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

If annual rainfall decreases by 15% accompanied by historical temperatures, such parameters indicate a decline in the climate suitability pattern and distribution for tobacco cultivation. When compared to the historical climate suitability patterns, Figure 18a above shows a considerable decline in the areas suitable for the growth of rainfed tobacco. Areas that had climate suitable for tobacco during the period 1990-2018 when exposed to a 15% decrease in precipitation indicate a decrease from being excellent into marginal, very marginal, and unsuitable as shown in Figure 18b. These areas will decrease in frequency from 20 911 (Figure 7b) to 16 477, see Figure 18b, which could have serious consequences on the country's economy. The southern part of the country is projected to range from marginal to unsuitable as shown in Figure 18a as the **belt** increases moving northwards covering large parts of Matebeleland South extending in Masvingo and small parts of Manicalandand Matabeleland North provinces and using frequencies shown on the histograms and 18b, the unsuitable areas also increase. Areas experiencing change are shown on Figure 18c (far right) above and theseare expected to experience a marginal to average decrease in suitability. A decrease in climate suitability will be experienced in the lower parts of the country including Matebeleland North, Matabeleland South, Bulawayo, part of Midlands, Masvingo and Manicaland Provinces.

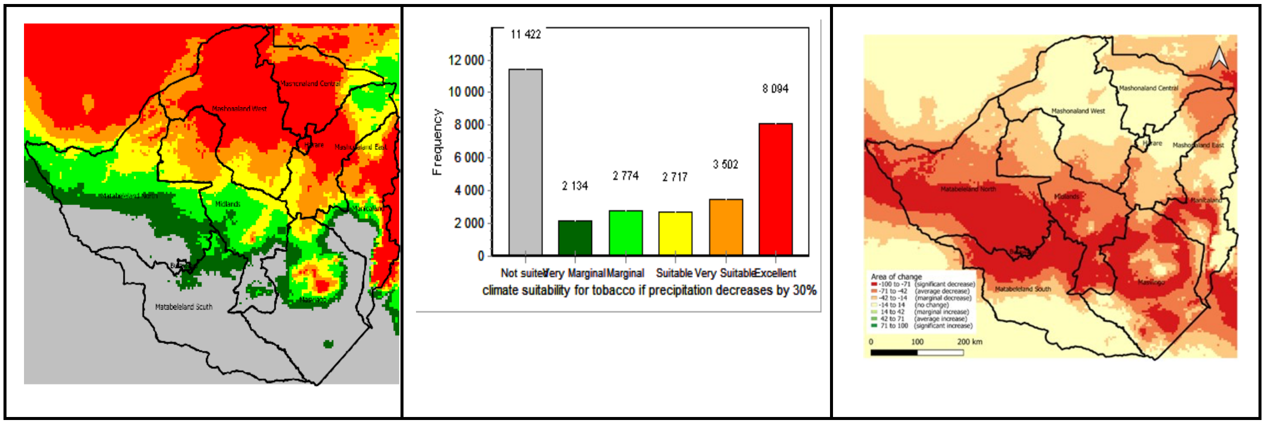


Figure 19 (left to right respectively) (a) shows the climate suitability for tobacco when precipitation decreases by 30% of the historical data(b) histogram representing the frequencies and distribution of climate suitability for tobacco if precipitation decreases by 30% (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

If precipitation decreases by 30% of the total average, the results could be disastrous on the climate suitability of tobacco cultivation, as shown in Figure 19a above. Figure 19a above shows a significant decline in the areas that once proved suitable for tobacco cultivation, this decline is shown by the frequency distribution (Figure 19b). These areas will be parts of Mashonaland West, Central, East, and Harare. Unsuitable areas based on climate patterns will increase in frequency, as shown in Figure 19b above, from 4 511 to 11 422, which is a significant change when compared to the historical patterns, and well shown on the map in Figure 19c (far right) above. Figure 19c shows that these areas will experience a marginal, average, and significant decrease in suitability if precipitation decreases by 30%. Unsuitable areas expand northwards, and the southern part of the country becomes unsuitable as the historical **belt** moves northwards into previously excellent areas because of precipitation decreases. These include Matebeleland South, Masvingo, part of Manicaland, Midlands and Matebeleland North, Mashonaland West, parts of Mashonaland East and Manicaland. These areas and other provinces that proved to be suitable historically are projected to shift into marginal and very marginal areas. This shift has direct implications on the country’s economic livelihood.

4.2.2 Spatial analysis of suitability resulting from increased average rainfall level

4.2.2.1 Maize

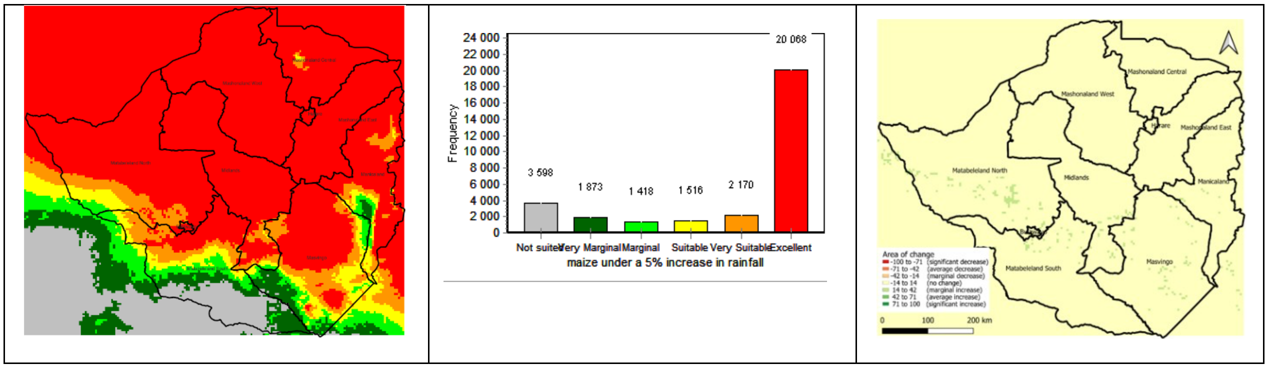


Figure 20 (left to right respectively). (a)shows the climate suitability for maize if precipitation increases by 5%(b) histogram representing the frequencies and distribution of climate suitability for maize if precipitation increases by 5% (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 20a above illustrates that, if rainfall increases by 5% of the historical average totals combined with historical temperatures, assuming they remain constant there will be a marginal increase in the areas suitable for the cultivation of maize. When compared to the historical climate suitability patterns, Figure 20a shows a marginal increase in the areas suitable for the growth of rainfed maize. Areas that had climate suitable for tobacco during the period 1990-2018 when exposed to a 5% increase in rainfall indicate a marginal increase in the frequency of the 'excellent' areas as shown on Figure 20b. The extent of suitability indicates a marginal increase in Figure 20a as the **belt** moves southwards covering large parts of Matebeleland South extending in Masvingo and small parts of Manicaland and Matabeleland North and using frequencies shown on the histogram, Figure 20b, the suitable areas also increase. Figure 20c shows the area that are likely to experience a change in suitability and these will include Matebeleland North, Matabeleland South, Bulawayo, part of Midlands, Masvingo and Manicaland provinces and the change shows to be very marginal.

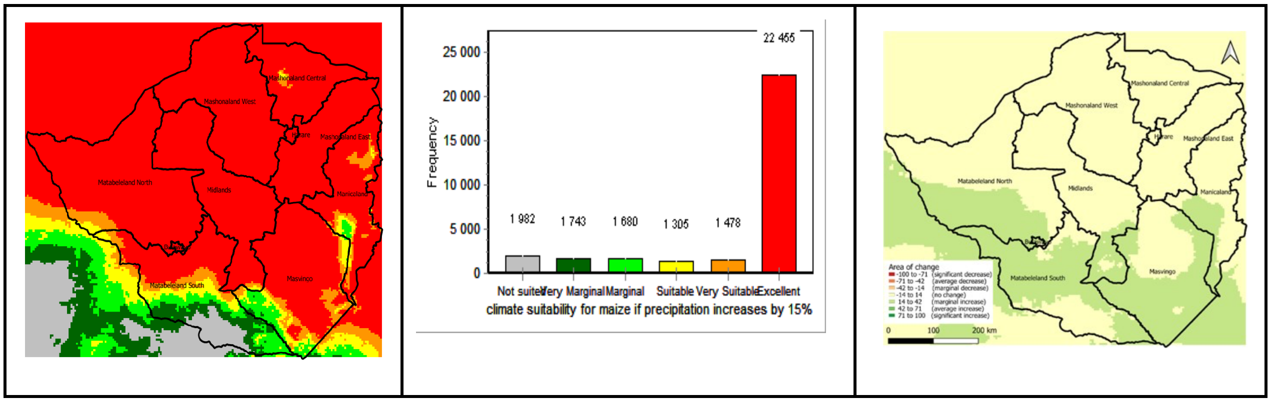


Figure 21a, b, c (left to right respectively). (a)shows the climate suitability for maize if precipitation increases by 15%(b) histogram representing the frequencies and distribution of climate suitability for maize if precipitation increases by 15% (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Climate change is expected to impose negative and positive impacts around different regions of the earth (IPCC, 2014). Regions lying within the tropics are expected to receive lower rainfall than usual; however, due to uncertainties that exist in climate change projections, these areas may receive an increase in the average annual precipitation although this is highly unlikely. In Zimbabwe, if precipitation increases by 15% and historical temperatures remain fixed, such climatic patterns show to be suitable for the cultivation of maize as shown in Figure 21a above. The regions that fall under the “excellent” class increase in frequency, from 18 729 (Figure 6b) to 22 455 as shown in Figure 21b above. These areas include Mashonaland West, Central, East Provinces, Harare, Bulawayo, Midlands; a larger part of Matebeleland North, Masvingo, Manicaland and a smaller part of Matebeleland South provinces. The unsuitable area also decreases in frequency as shown in Figure 21b above. When compared with the historical climate suitability, the areas that will experience both slight and significant increase when subjected to a 15% increase in precipitation are shown on Figure 16c above.

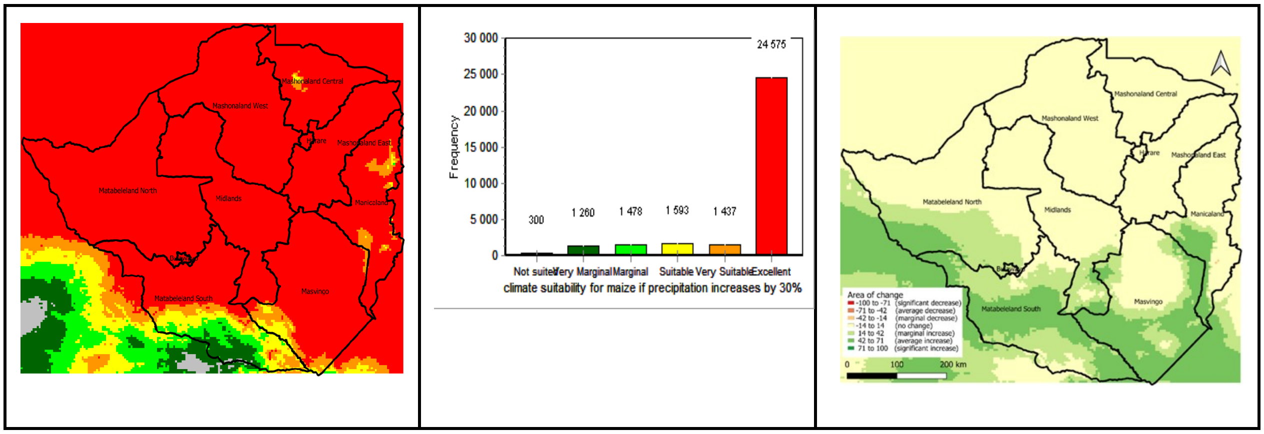


Figure 22a, b, c (left to right respectively). (a)shows the climate suitability for maize if precipitation increases by 30%(b) histogram representing the frequencies and distribution of climate suitability for maize if precipitation increases by 30%. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

In Zimbabwe, if precipitation increases by 30% during the growing season and historical temperatures remain constant, such climatic patterns prove to be very suitable for the cultivation of maize as shown in Figure 22a above. The regions that fall under the "excellent" class will increase in terms of frequency as shown on Figure 22b above when compared with the historical pattern. These areas include Mashonaland West, Central, East Provinces, Harare, Bulawayo, Midlands; a larger part of Matebeleland North, Masvingo, Manicaland and a smaller part of Matebeleland South as shown on Figure 22a above. Figure 22c shows that the areas along the **belt** will experience both marginal to average increase under a 30% increase in annual precipitation when compared to the historical climate suitability. If precipitation increases by 30%, the **belt** decreases in size moving southwards thereby increasing the extent of excellent areas, *see* Figure 22a and thereby reducing unsuitable areas. Within provinces like Mashonaland central, Masvingo and Manicaland the climatic suitability in some areas will range between suitable and very suitable. The unsuitable area even decreases in frequency as shown on Figure 22b above. However, when Figure 22c is compared to 21c above, there is a difference in amplitude because of different rainfall changes. When rainfall increases by 15%, parts of Matebeleland South will remain unsuitable as compared to under a 30% increase.

4.2.2.2. Tobacco

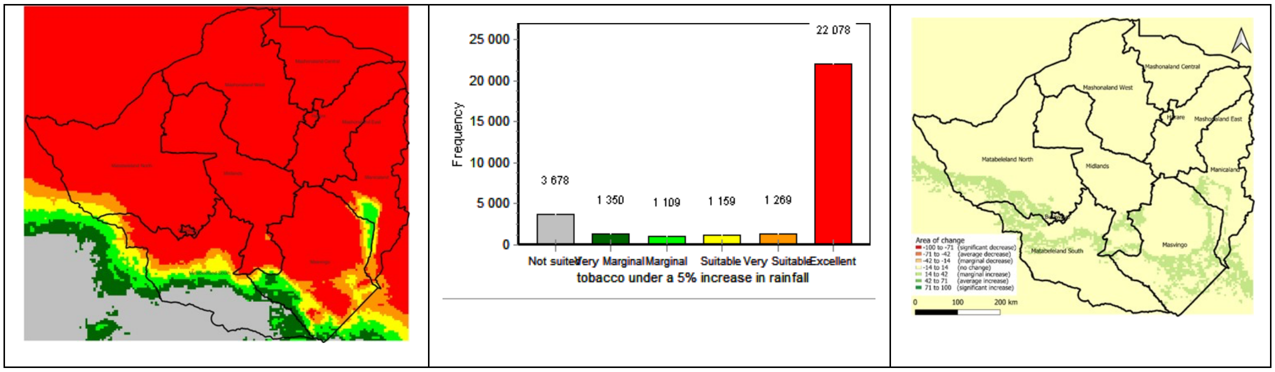


Figure 23a, b, c (left to right respectively). (a)shows the climate suitability for tobacco if precipitation increases by 5%(b) histogram representing the frequencies and distribution of climate suitability for tobacco if precipitation increases by 5%(c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 23a above shows that, if precipitation increases by 5% of the historical annual averages combined with fixed historical temperatures, a large part of the country will likely be excellent for the cultivation of tobacco, and they will increase in frequency from 20 911 (Figure 7b) to 22 078 as shown on Figure 23b above. The**belt** also decreases into the southern parts of the country and the areas that will experience changesare presented on the map on Figure 23c above and this increase will be marginal. The areas likely to experience the marginal increase include, Bulawayo, Matabeleland North, Matabeleland South, Midlands, parts of Manicaland, and Masvingo. Compared with the historicaloutput, Figure 23a illustrates those small parts of the region will range between very suitable andvery marginal and Matebeleland South Province will lie within these conditions. Areas not suitedwill decrease in frequency and this will be in Matebeleland South.

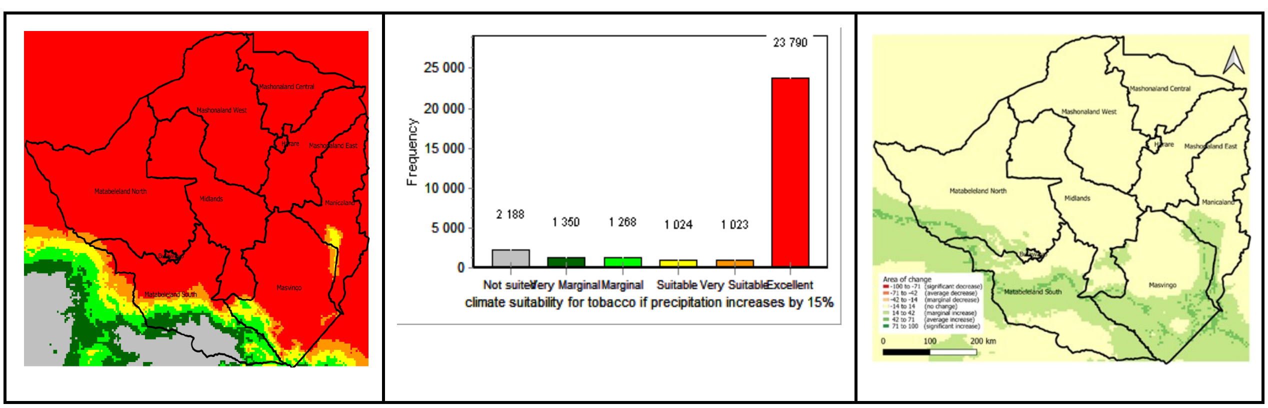


Figure 24 (left to right respectively). (a)shows the climate suitability for tobacco if precipitation increases by 15%(b) histogram representing the frequencies and distribution of climate suitability for tobacco if precipitation increases by 15% (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Furthermore, suppose precipitation increases by 15% of the historical annual averages accompanied by fixed historical temperatures, large parts of the country will likely remain excellent for tobacco cultivation (see Figure 24a). In that case, they will increase in frequency, as shown in Figure 24b above. The **belt** decreases southwards into previously unsuitable areas, resulting in large parts of the country becoming suitable for tobacco cultivation. The areas that will experience changes are presented on the map in Figure 24c (far right) above, and this change will likely range between marginal and average increases. These areas will include Bulawayo, Matabeleland North, Matabeleland South, Midlands, parts of Manicaland and Masvingo. In contrast with the historical output, Figure 24a illustrates those small parts of the country that will range between very suitable and unsuited, and this will be in Matebeleland South Province.

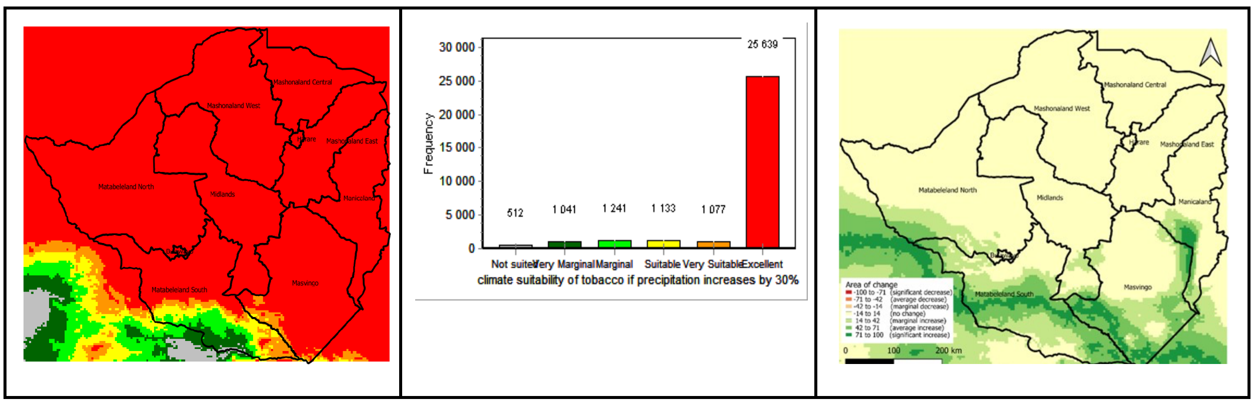


Figure 25 (left to right respectively). (a)shows the climate suitability for tobacco if precipitation increases by 30%(b) histogram representing the frequencies and distribution of climate suitability for tobacco if precipitation increases by 30%. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

If precipitation increases by 30% of the historical annual averages during the growing season accompanied by fixed historical temperatures, large parts of the country will likely be suitable for tobacco cultivation (see Figure 25a), and they will also increase in frequency, as shown on Figure 25b above. These areas will include Bulawayo, Matabeleland North, Midlands, Mashonaland West, Harare, Mashonaland Central, East, more prominent parts of Manicaland, and Masvingo. Compared with the historical output, Figure 25a illustrates that the **belt** will descend southwards and reduce in size, resulting in a small part of the country ranging from very suitable to very marginal, and the historically unsuitable areas will become suitable especially in Matabeleland South province. Figure 25c represents the areas that will experience a marginal to significant increase compared to the historical output. These areas include part of Matebeleland North, Manicaland, large parts of Matebeleland South, and Masvingo provinces.

4.3 Combination of increased temperature and variations in precipitation averages.

This section shall present a combination of increased temperature variations and +/-5% and +/-30% precipitation averages because they are the averages showing a distinct difference. A combination of the increased temperature variations and +/-15% precipitation is presented in the appendices below for reference.

4.3.1. Spatial analysis of suitability sensitivity resulting from a combination of a 2ºC temperature increase and +/-5%, +/-30% precipitation variations.

4.3.1.1. Maize

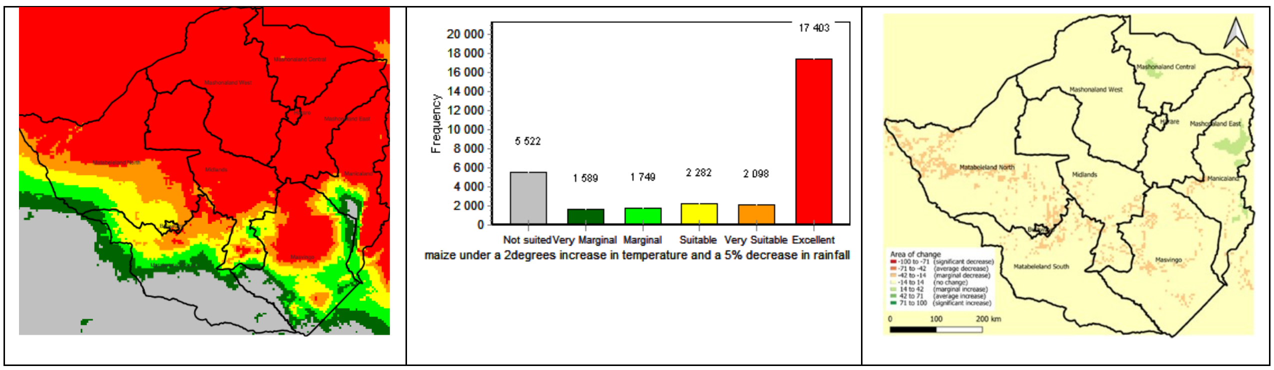


Figure 26. (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 2ºC combined with a decrease in rainfall by 5%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 5% decrease in rainfall and a 2ºC temperature increase. (c) shows areas of change when compared to the historical outputs.

If temperatures increase by 2ºC combined with a 5% decrease in annual average precipitation, such climatic patterns are less likely to affect the cultivation of maize, as shown in Figure 26a. Regions that once showed excellent suitability based on climate patterns will reduce in frequency, from 18 729 (Figure 6b) to 17 403 as illustrated in Figure 26b. These areas will include Mashonaland East, Manicaland, Midlands, and a small part of Matebeleland North. Other parts will range between very marginal and very suitable, including parts of Matabeleland North and South, southern parts of Midlands and Manicaland, and Masvingo. A considerable part of the country will become unsuitable for promoting the growing of maize, mainly Matabeleland South extending into Masvingo and smallerparts of Manicaland. Compared to the historical climate suitability, Figure 26c shows the provincesthat will undergo marginal decrease and marginal increase (using the legend on *Insert 1* above). These areas include very small parts of Mashonaland Central, Manicaland, Matabeleland Northand South, and Masvingo provinces.

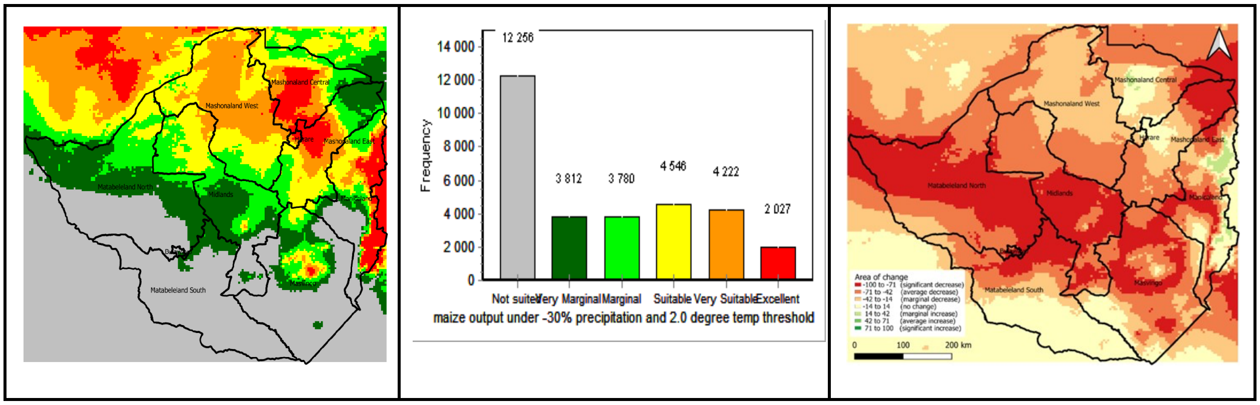


Figure 27 (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 2°C combined with a decrease in rainfall by 30%, (b) a histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 30% decrease in rainfall and a 2°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate

However, suppose a 2°C temperature increase is combined with a 30% decrease in the average precipitation in that case, such climatic conditions are unsuited for the cultivation of maize during the growing season, as shown in Figure 27a above. As such, this can negatively impact the country's agricultural sector and consequently affect the economy. Areas that were once suitable will shift mostly to become unsuited. These include almost all Matebeleland South, a large partof Masvingo and Matebeleland North, and a small part of Midland, and Manicaland Province. Thisis also shown by the change in the position of the **belt**, which ascends northwards. The extent ofareas of 'excellent' suitability will significantly decrease to cover small parts of Mashonaland Central, East and Harare and Manicaland Province. The distribution of marginal and very marginalareas also increases, as shown in Figure 27b above. These areas will include large parts of Matebeleland South and Midlands Province, small parts of Masvingo stretching into Manicaland, and a significant part of Mashonaland East. Figure 27c above shows that, compared to the historical outputs, large parts of the country will experience a marginal to a significant decrease inclimate patterns suitable for the growth of maize. These areas will include large parts of Matebeleland North, Midlands, Mashonaland West, Masvingo, Mashonaland East, Manicaland, and the whole province of Matabeleland South will become largely unsuited for the growth of maize.

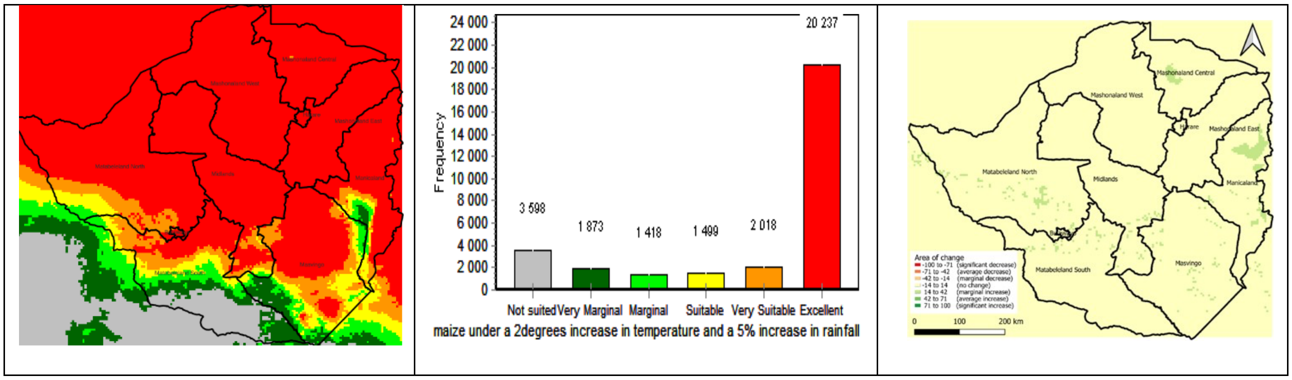


Figure 28 (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 2.0 ºC combined with an increase in precipitation by 5% (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 5% increase in precipitation and a 2.0 ºC temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate

The map above, Figure 28a, shows the climate suitability for maize if temperatures increase by 2ºC accompanied by a 5% increase in the average annual precipitation received in the country. Based on the models' simulations, such climatic parameters present a marginal increase in suitability for maize cultivation in the country, as shown in Figure 28c above. Regions that once showed excellent suitability based on climate patterns will slightly increase in frequency, from 18 729 (Figure 6b) to 20 237 as illustrated in Figure 28b above. The position of the **belt** extends southwards, resulting in a smaller part of the country becoming unsuitable for promoting the growing of maize, mainly in Matabeleland South. Meanwhile, other parts of the country will experience a marginal increase insuitability under such climate conditions. This increase will be in Provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, much of Matebeleland North, Masvingo, andManicaland.

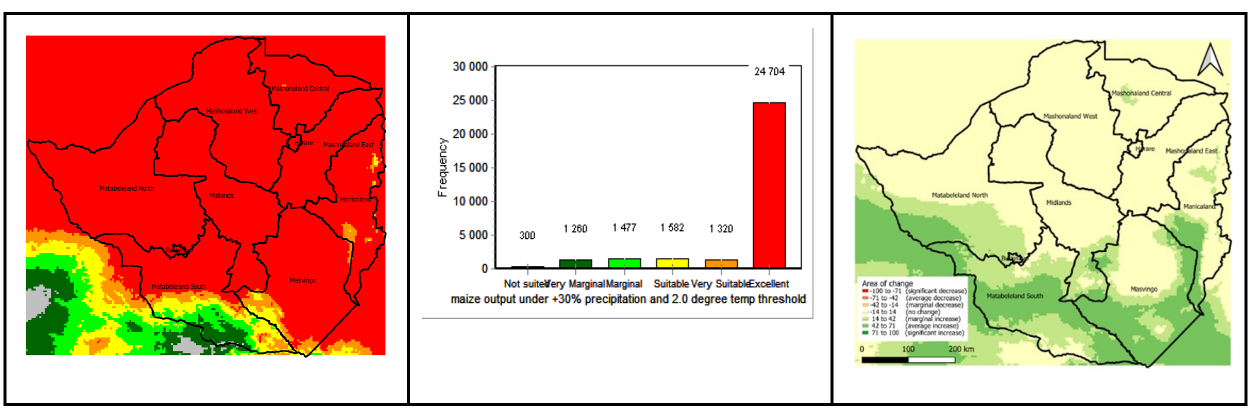


Figure 29(left to right respectively). (a) shows the climate suitability of maize if temperature increases by 2.0 ºC combined with an increase in precipitation by 30% (b) histogram representing the frequencies and distribution of climate suitability for maize *under a combination of a 30% increase in precipitation and a 2.0 °C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.*

Figure 29a above shows the climate suitability for maize if temperatures increase by 2°C accompanied by a 30% increase, although highly unlikely, in the average annual precipitation received in the country. Based on the models' simulations, such climatic parameters are suitable for cultivating maize in some provinces of the country. These climate conditions will be excellent in provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, much of Matebeleland North, Masvingo, and Manicaland. The position of the **belt** extends southwards, resulting in the extent of these excellent areas becoming more prominent than the historical patterns, which could consequently lead to food security within the country. Small parts of Manicaland, Masvingo, and Matabeleland North will likely have some areas ranging from very marginal to very suitable, as shown by the frequencies in Figure 29b. Matebeleland South Province, however, despite the precipitation increase, will have other parts remaining unsuited for maize cultivation. Figure 29c above shows the provinces that will likely experience a marginal to average increase under a 2°C temperature increase and a 30% increase in average annual precipitation. The areas that will change are mostly in the southern part of the country, including Matebeleland North, South, and Masvingo, exception for small parts of Midlands, Mashonaland Central, and Manicaland Provinces, which do not lie within the southern part of the country.

4.3.1.2. Tobacco

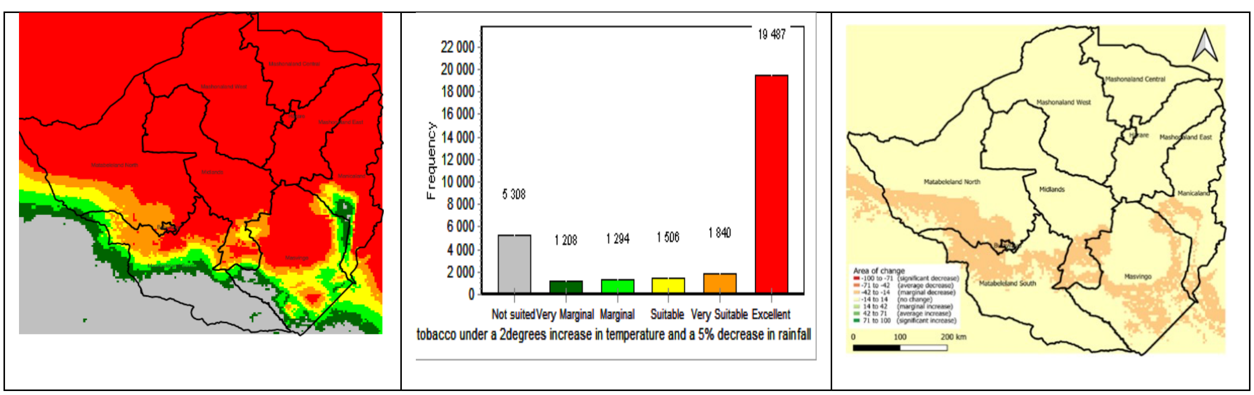


Figure 30 (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 2°C combined with a decrease in rainfall by 5%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 5% decrease in rainfall and a 2°C temperature increase. (c) shows areas of change when compared to the historical outputs.

If temperatures increase by a 2°C combined with a 5% decrease in annual average precipitation, such climatic patterns will be marginally suitable for tobacco cultivation, as shown in Figure 30a above. The position of the **belt** extends north-east, and regions that once showed to be excellentin terms of suitability based on climate patterns will reduce in size from a frequency, from 20 911 (Figure 7b) to 19 487 in Figure 30b. These areas will include Mashonaland West, Harare, Mashonaland Central, East, and parts of Masvingo, Manicaland, Midlands, and a small part of Matebeleland North. The unsuitable areas will increase in the frequency of occurrence, as shown in Figure 30b above, although the increase is marginal. Figure 30c above shows the provinces that will likely experiencea marginal decrease in suitability. These areas will be parts of Matabeleland North and South, Bulawayo extending into Masvingo, Manicaland, Midlands, and Manicaland provinces.

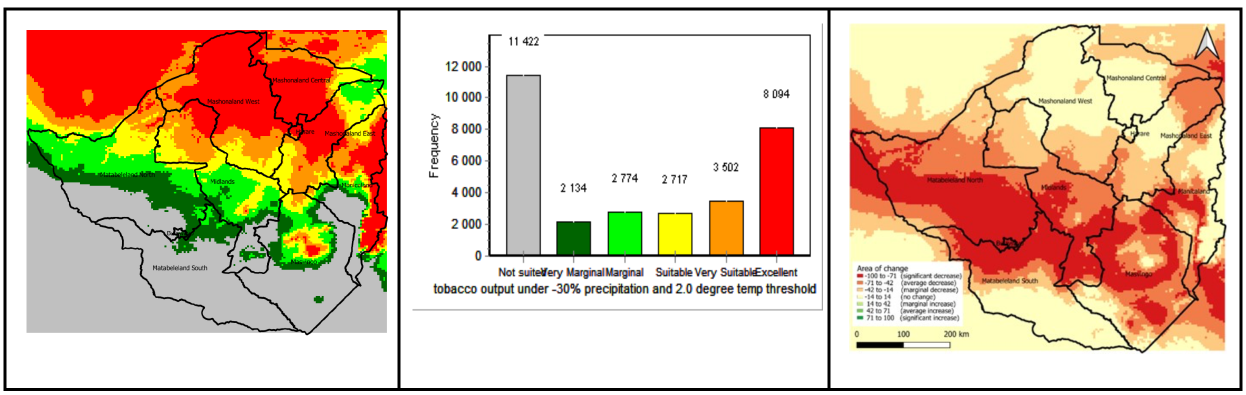


Figure 31 (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 2.0 °C increase combined with a decrease in precipitation by 30%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 30% decrease in precipitation and a 2.0 °C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Furthermore, Figure 31a above shows the climate suitability for tobacco if the temperature increases by a 2°C accompanied by a 30% decrease in precipitation. Such climatic patterns show to be significantly unsuitable for the cultivation of tobacco. The **belt** in Figure 31a above extends north-east and areas that were historically ‘excellent’ in terms of suitability decrease in size (see Figure 31c) only to cover Provinces such as Mashonaland West, Central, small parts of Mashonaland East, Manicaland, and Harare. Lower parts of the country, including Matebeleland South, Bulawayo, Masvingo; part of Matebeleland North, Midlands, and Manicaland provinces, will become unsuitable if such climatic parameters prevail. Other parts of these provinces will range from verymarginal to very suitable. The map in Figure 31c shows the provinces that will likely change compared to the historical output. The areas that will experience a marginal to a significant decrease in suitability include parts of Matebeleland North, Matebeleland South, Midlands, Mashonaland West, Mashonaland East, Bulawayo, Masvingo, and Manicaland provinces.

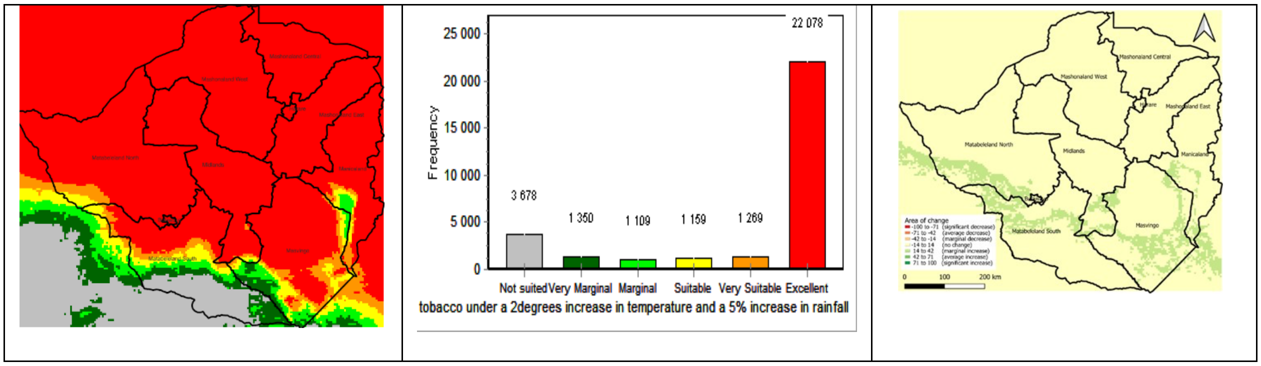


Figure 32 (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 2°C combined with an increase in rainfall by 5%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 5% increase in rainfall and a 2°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 32a above shows the climate suitability for tobacco if the annual precipitation increases by 5% and temperatures increase by 2°C. The models simulate that such climatic parameters are marginally suitable for the growth of tobacco in the country. These climate conditions will be excellent in Provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, much of Matebeleland North, Masvingo, and Manicaland provinces, and the extent of these areas is larger than that of the historical patterns, and they could consequently improve the economic situation within the country. The frequency of this suitability increases marginally when compared to that of the historical patterns, as shown in Figure 32b. Small parts of Manicaland, Masvingo, and Matabeleland North will, however, have some areas ranging from very marginal to very suitable, as shown by the frequencies in Figure 32b. Matebeleland South Province, however, despite the precipitation increase, will have other parts not being suited for tobacco cultivation. Smaller parts of the southern region of the country are likely to experience a marginal increase in suitability, as shown in Figure 32c.

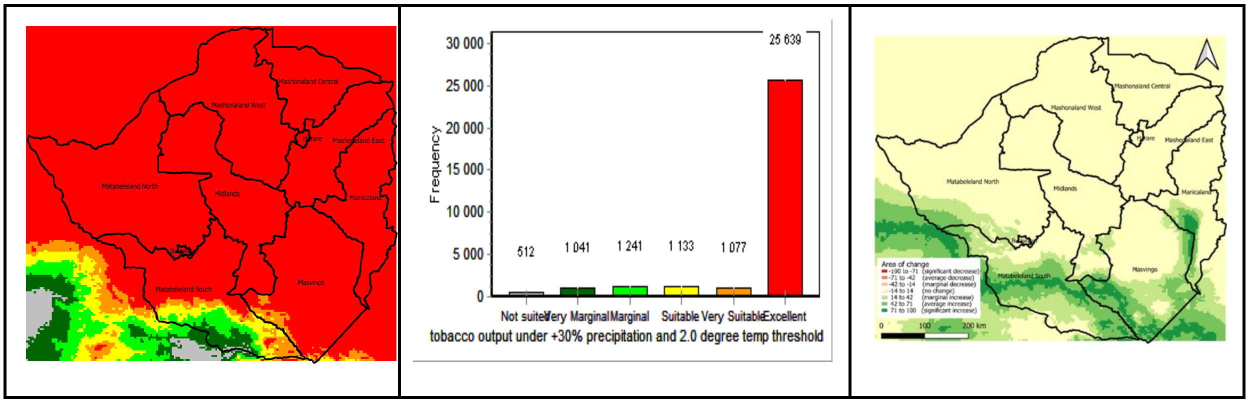


Figure 33 (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by a 2°C combined with an increase in precipitation by 30%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 30% increase in precipitation and a 2°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 33a, shows the climate suitability for tobacco if the annual precipitation increases by 30% and temperatures increase by 2°C. The models simulate that such climatic parameters are suitable for the growth of tobacco in the country. The position of the **belt** extendssouthwards, resulting in Provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, most of Matebeleland North, Masvingo, and Manicaland experiencing excellent conditions for tobacco cultivation. The extent of these areas is projected to become more extensive than the historical patterns, and they could consequently improve the economic situation within the country, *see* Figure 33b. The frequency of this suitability increases from marginal to significantwhen compared to the historical patterns, as shown in Figure 33c. The parts that will experience asignificant increase when exposed to such climatic patterns include a small part of Matebeleland South, extending into Masvingo and Manicaland provinces, as shown on Figure 33c above. Matebeleland South Province, however, despite the precipitation increase, will have other parts not being suited for tobacco cultivation.

4.3.2. Spatial analysis of suitability sensitivity resulting from a combination of 3°C temperature increase and +/- 5%, +/-30% precipitation variations.

4.3.2.1. Maize

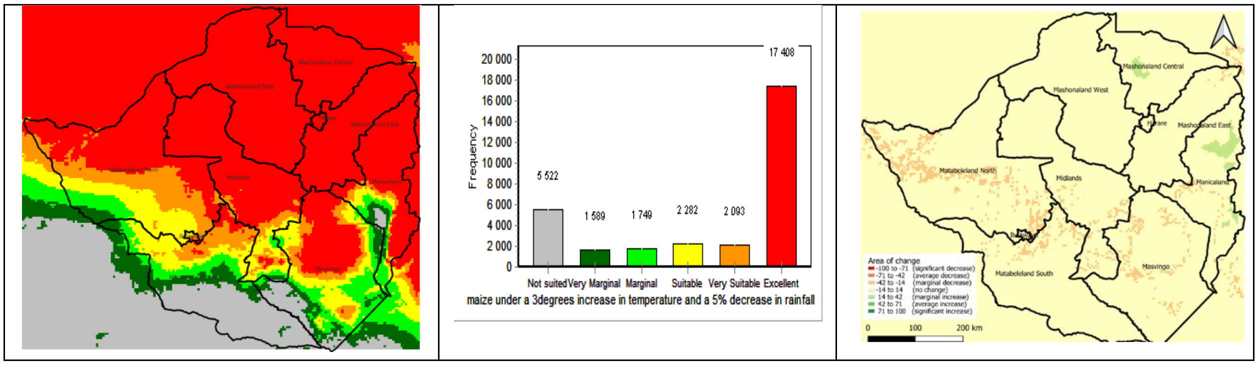


Figure 34. (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 3°C combined with an decrease in precipitation by 5%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 5% decrease in precipitation and a 3°C temperature increase. (c) shows areas of change when compared to the historical outputs.

Suppose temperatures increase by 3°C combined with a 5% decrease in annual average precipitation, suchclimatic patterns are projected to be less likely to affect the cultivation of maize, as shown in Figure34a above when compared to the historical patterns. Regions that once showed excellent suitabilitybased on climate patterns will marginally decrease in frequency from 18 729 (Figure 6b) to 17 408 as illustrated on Figure 34b above.These areas will include Mashonaland West, Harare, Mashonaland Central, East, and parts of Masvingo, Manicaland, Midlands, and a small part of Matebeleland North provinces. Other parts will rangebetween very marginal and very suitable, including parts of Mashonaland Central and East. A small part of the country will become unsuitable for promoting the growing of maize, mainly Matabeleland South extending into Masvingo and smaller parts of Manicaland. When compared to the historical climate suitability, Figure 34c shows the provinces that will undergo marginal decrease and marginal increase (using the legend on *Insert 1* above). These areas include very small parts of Mashonaland Central, Manicaland, Matabeleland North and South, and Masvingo provinces.

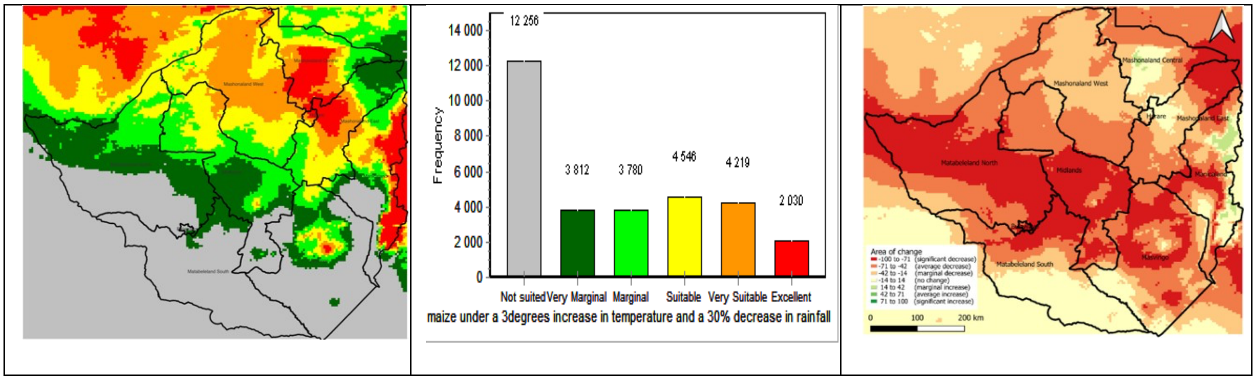


Figure 35 (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 3°C combined with a decrease in precipitation by 30%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 30% decrease in precipitation and a 3°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

When a 3°C temperature increase is accompanied by a 30% decrease in the average precipitation, such climatic conditions are unsuitable for maize cultivation during the growing season, as shown in Figure 35a above. As such, this can negatively impact the country's agricultural sector and consequently affect food security and people's livelihoods. Areas that were once suitable will shift mostly to become unsuited. These include almost all of Matabeleland South, a prominent part of Masvingo and Matabeleland North, a small part of Midlands, and Manicaland Province. The extent of areas with 'excellent' suitability will decrease to cover small parts of Mashonaland Central, East, Harare, and Manicaland Province. The **belt** in Figure 35a will expand northwards, and the distribution of marginal and very marginal increases, as shown in Figure 35b above. These areas will include large parts of Matabeleland South and Midlands Province, small parts of Masvingo stretching into Manicaland, and a significant part of Mashonaland East. Figure 35c above shows that, when compared to the historical outputs, large parts of the country will experience a slight, marginal, and significant decrease in climate patterns suitable for the growth of maize. These areas will include large parts of Matebeleland North, Midlands, Mashonaland West, Masvingo, Mashonaland East, Manicaland, and the whole province of Matabeleland South will become largely unsuited for the growth of maize.

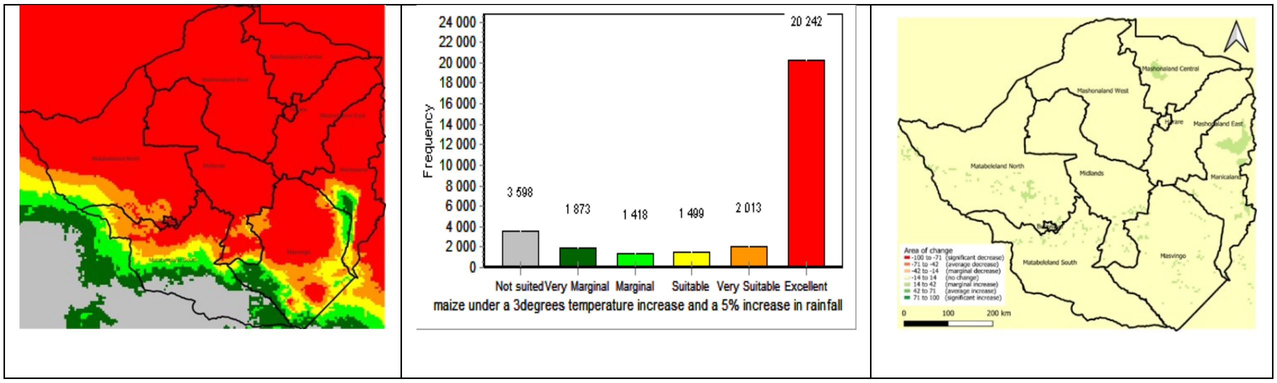


Figure 36. (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 3ᵒC combined with an increase in rainfall by 5%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 5% increase in rainfall and a 3ᵒC temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

The map above, Figure 36a, shows the climate suitability for maize if temperatures increase by 3ᵒC accompanied by a 5% increase in the average annual precipitation received in the country. Based on the models' simulations, such climatic parameters present a marginal increase in suitability for maize cultivation in the country, as shown in Figure 36c above. Regions that once showed to be excellent in terms of suitability based on climate patterns will marginally increase in frequency, from 18 729 (Figure 6b) to 20 242 as illustrated in Figure 36b above. The position of the **belt** extends southwards, resulting in a smaller part of the country becoming unsuitable for promoting the growing of maize,mainly Matabeleland South province. Meanwhile, other parts of the country will experience a marginal increase in suitability under such climate conditions. This increase will be in small parts of provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, much of Matebeleland North, Masvingo, and Manicaland.

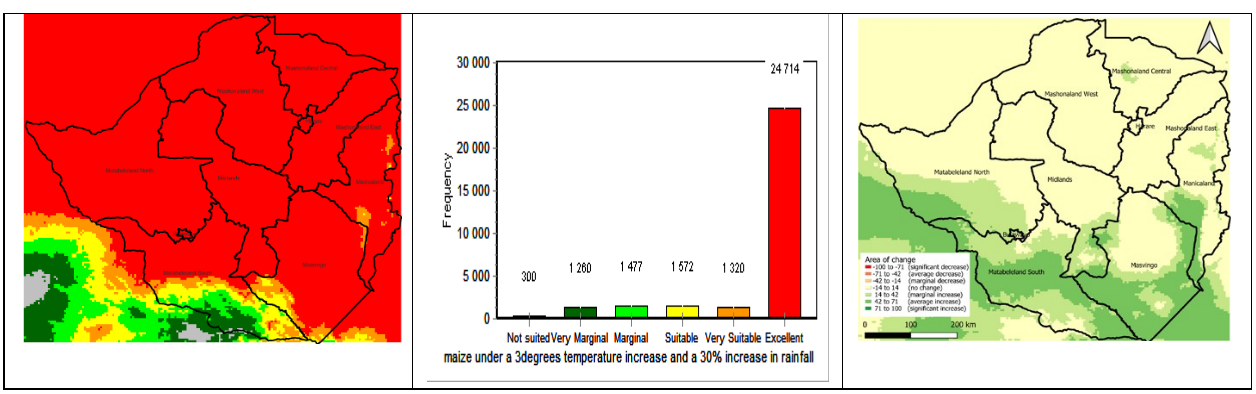


Figure 37.(left to right respectively). (a) shows the climate suitability of maize if temperature increases by 3 ᵒC combined with an increase in rainfall by 30%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a

combination of a 30% increase in rainfall and a 3°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Meanwhile, Figure 37a above shows the climate suitability for maize if temperatures increase by 3°C accompanied by a 30% increase in the average annual precipitation received in the country. Such climatic parameters are projected to be suitable for the cultivation of maize in some provinces of the country. These climate conditions will be excellent in Provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, much of Matebeleland North, Masvingo, and Manicaland, as shown in Figure 37a above. The position of the **belt** extends southwards, resulting in the extent of these excellent areas becoming larger than that of the historical patterns,and this could potentially promote food security in the country. Small parts of Manicaland, Masvingo, and Matabeleland North will likely have some areas ranging from very marginal to very suitable, as shown by the frequencies in Figure 37b. Matebeleland South Province, however, despite the precipitation increase, will have other parts unsuited for the maize crop. Figure 37c above shows the provinces that will likely experience a marginal to an average increase under a 3°C temperature increase and a 30% increase in average annual precipitation. The areas that will likely experience a marginal to average increase in suitability include Matebeleland North, South,Masvingo, and small parts of Midlands, Mashonaland Central, and Manicaland Provinces, see Figure 37c.

4.4.2.2. Tobacco

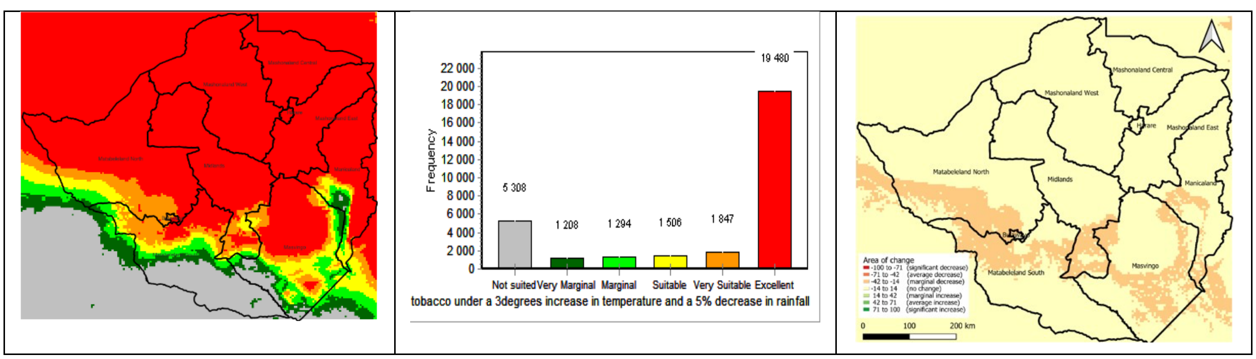


Figure 38. (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 3°C increase combined with an decrease in rainfall by 5%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 5% decrease in rainfall and a 3°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 38a above shows that if temperatures increase by 3°C and are combined with a 5% decrease in annual average precipitation, such climatic patterns will be marginally unsuitable for tobacco cultivation. The position of the **belt** extends northwards, and regions that once showed to be excellent in terms of suitability based on climate patterns will marginally reduce in size as shown by the frequency distribution, from 20 911 (Figure 7b) to 19 480 as illustrated on Figure 38b above. These areas will include parts of Masvingo, Manicaland, Midlands, and a small part of Matebeleland North provinces. A prominent part of the country will remain unsuitable for the growth of tobacco. Figure 38c above shows the provincesthat will experience change under such climatic conditions. These are mainly Matabeleland northextending into Matebeleland south, Masvingo, Manicaland, Midlands, and Manicaland. The unsuitable regions will increase in the frequency of occurrence.

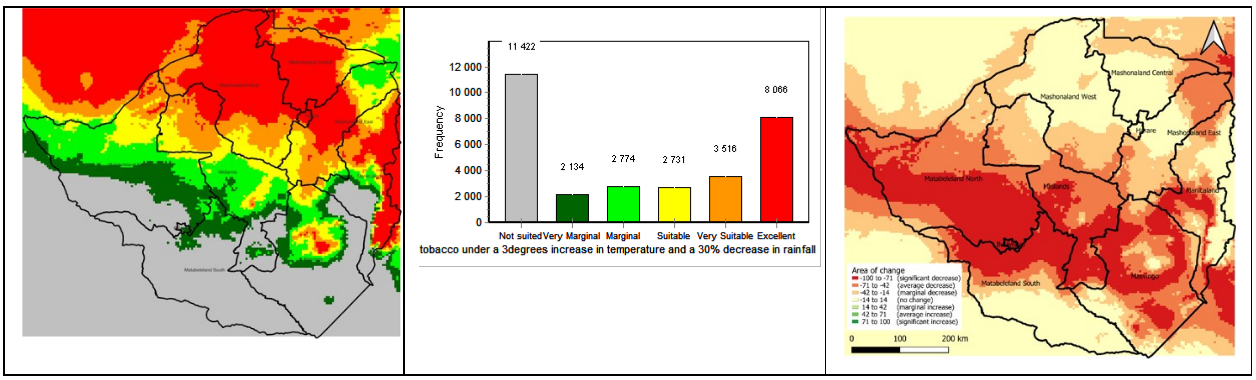


Figure 39. (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 3 °C combined with a decrease in precipitation by 30%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 30% decrease in precipitation and a 3°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Furthermore, Figure 39a above shows the climate suitability for tobacco if temperatures increase by a 3°C accompanied by a 30% decrease in precipitation. Such climatic patterns are projected as significantly unsuitable for tobacco cultivation. The **belt** in Figure 39a above extends north-east and areas that were historically 'excellent' in terms of suitability decrease in size (see Figure 39c) only to cover Provinces such as Mashonaland West, Central, small parts of Mashonaland East, Manicaland and Harare. Lower parts of the country, including Matebeleland South, Bulawayo, Masvingo; part of Matebeleland North, Midlands, and Manicaland, will become unsuitable if such climatic parameters prevail. Other parts of these Provinces will range from very marginal to very suitable. The map in Figure 39c shows the provinces that will likely change when compared to the historical output. The areas that will experience a marginal to a significant decrease in suitability include parts of Matebeleland North, Matebeleland South, Midlands, Mashonaland West, Mashonaland East, Bulawayo, Masvingo, and Manicaland.

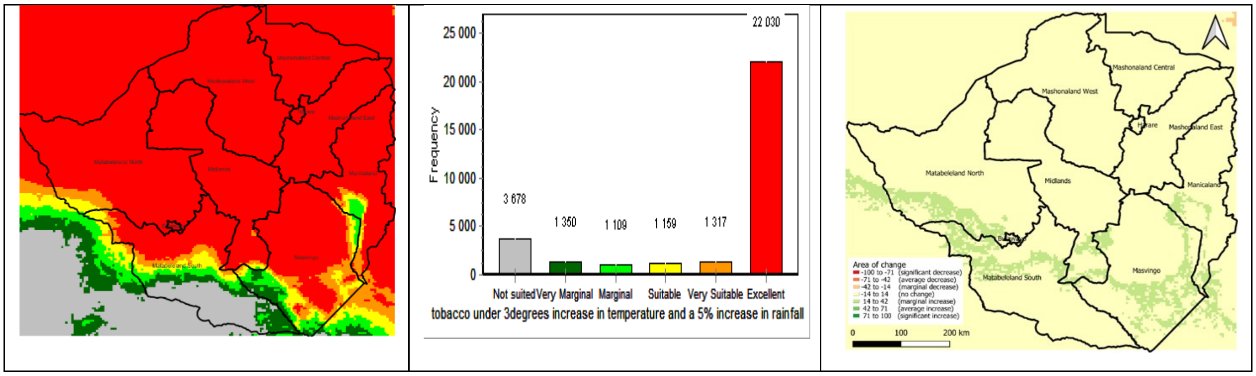


Figure 40. (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 3°C increase combined with an increase in rainfall by 5%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 5% increase in rainfall and a 3°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 40a above shows the climate suitability for tobacco if the annual precipitation increases by 5% and temperatures increase by 3°C. The models simulate that such climatic parameters are marginally suitable for the growth of tobacco in the country. The positions of the **belt** recede southwards into previously unsuitable areas. These climate conditions will be excellent in Provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, much of Matebeleland North, Masvingo, and Manicaland, and this extent is larger than the historical patterns, see Figure 40b. Matebeleland South will have other parts remaining unsuitable under such climatic parameters. A small part of the country, in the south, will likely experience a marginal increase in suitability, as shown in Figure 40c above.

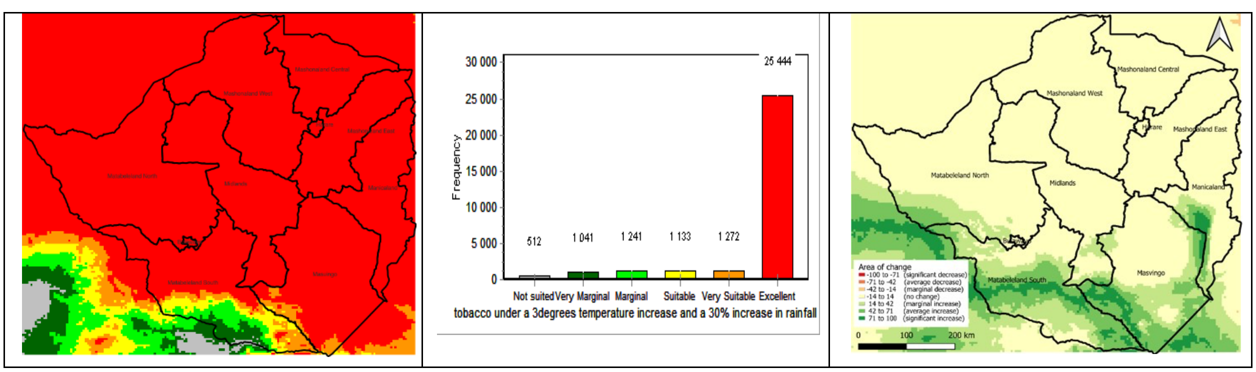


Figure 41. (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 3°C increase combined with an increase in rainfall by 30%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 30% increase in rainfall and a 3°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 41a above shows the climate suitability for tobacco if the annual precipitation increases by 30% and temperatures increase by 3°C. The models simulate that such climatic parameters are suitable for the growth of tobacco in the country. The position of the **belt** extends southwards, resulting in Provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, most of Matebeleland North, Masvingo, and Manicaland experiencing excellent conditions for the cultivation of tobacco. The extent of these areas is projected to become larger than that of the historical patterns, and they could potentially improve the economic situation within the country, *see* Figure 41b. The frequency of this suitability increases from marginal to significant compared to historical patterns, as shown in Figure 41c. The parts that will experience a significant increase when exposed to such climatic patterns include a small part of Matebeleland North and South, extending into Masvingo and Manicaland, as shown in Figure 41c above. Some parts of Matebeleland South, however, despite the precipitation increase, will have other parts not suited for tobacco cultivation.

4.3.3. Spatial analysis of suitability sensitivity resulting from a combination of 4.0 °C temperature increase and +/-5%, +/-30% precipitation variations.

4.3.3.1. Maize

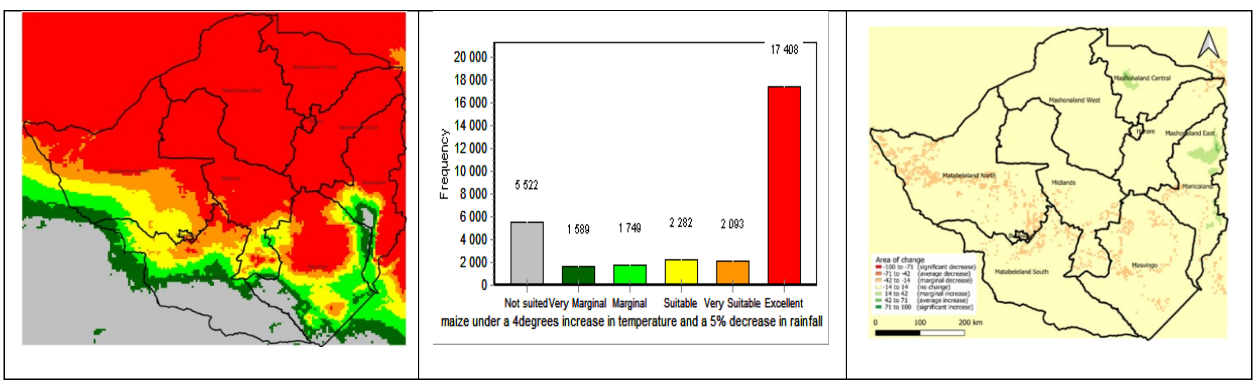


Figure 42 (left to right respectively). (a) shows the climate suitability of maize if temperature increases by a 4.0 °C increase combined with a decrease in precipitation by 5%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 5% decrease in precipitation and a 4.0 °C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Furthermore, if temperatures increase by 4°C and are combined with a 5% decrease in annual average precipitation, such climatic patterns are projected to be marginally unsuitable for maize cultivation, as shown in Figure 42a above. When compared to the historical climate patterns, regions that were once shown to be excellent in terms of suitability based on climate patterns will reduce in frequency, from 18 729 (Figure 6b) to 17 488 as illustrated in Figure 42b above. A prominent part of the country will become unsuitable for promoting the growth of the maize crop, mainly Matabeleland South extending into Masvingo and smaller parts of Manicaland and Matebeleland North. When compared to the historical climate suitability, Figure 42c shows the provinces that will undergo amarginal increase, and these include parts of Mashonaland Central and Manicaland. However, most areas will experience a marginal decrease, and these include Matabeleland North and South, Bulawayo, Midlands, Masvingo, part of Manicaland, and Mashonaland East Provinces.

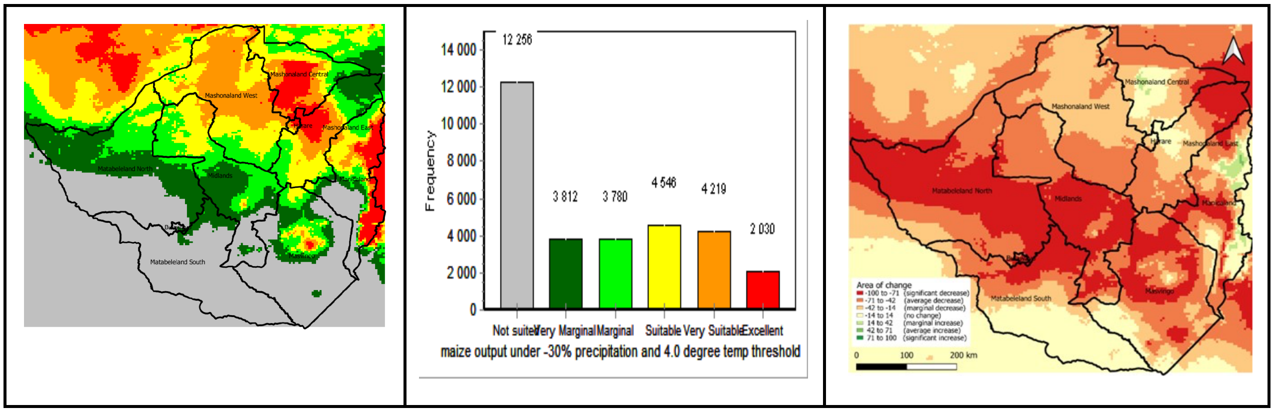


Figure 43 (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 4°C combined with a decrease in precipitation by 30%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 30% decrease in precipitation and a 4°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Suppose a 4°C temperature increase is accompanied by a 30% decrease in the average precipitation, in that case, such climatic conditions are unsuitable for the cultivation of maize during the growing season, as shown in Figure 43a above. As such, this can negatively impact the agricultural sector of the country and inevitably threaten food security. Areas that were once suitable will likely shift to become unsuited, including almost all of Matabeleland South, a large part of Masvingo and Matabeleland North, and a small part of Midlands and Manicaland Province. The extent of areas with 'excellent' suitability will decrease to cover small parts of Mashonaland Central, East, Harare, and Manicaland Province. The **belt** in Figure 43a expands northwards, resulting in a significant part of the country becoming unsuited. The distribution of marginal and very marginal also increases, as shown in Figure 43b above. These areas will include large parts of Matabeleland South and Midlands Province, a small part of Masvingo advancing into Manicaland, and a significant part of Mashonaland East. Figure 43c above shows that, when compared to the historical outputs, large parts of the country will experience a marginal to a significant decrease in climate patterns that are suitable for the growth of maize. These areas will include large parts of Matebeleland North, Midlands, Mashonaland West, Masvingo, Mashonaland East, Manicaland, and the whole province of Matabeleland South will become largely unsuited for the growth of maize.

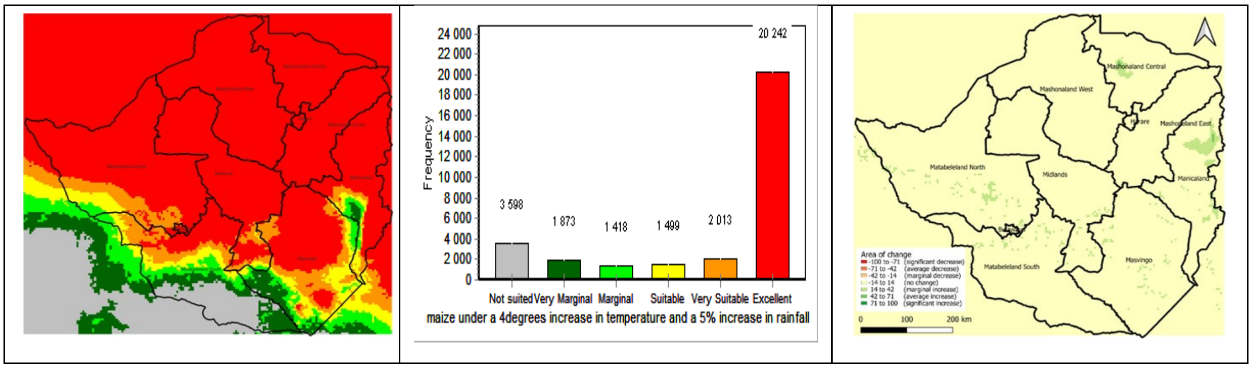


Figure 44 (left to right respectively). (a) shows the climate suitability for maize if temperature increases by 4.0 °C combined with an increase in precipitation by 5%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 5% increase in precipitation and a 4°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 44a above shows the climate suitability for maize if temperatures increase by 4°C accompanied by a 5% increase in the average annual precipitation received in the country. Based on the models' simulations, such climatic parameters are marginally suitable for the growth of maize in the country, see Figure 44c above. These climate conditions will remain excellent in provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, much of Matebeleland North, Masvingo, and Manicaland, and the area is slightly larger than the historical patterns, from 18 729 (Figure 6b) to 20 242, see Figure 44b. The position of the **belt** extends southwards, resulting in a smaller partof the country becoming unsuitable for promoting maize cultivation, mainly Matabeleland South.Meanwhile, other parts of the country will experience a marginal increase in suitability under suchclimatic conditions. This increase will be in small parts of provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, much of Matebeleland North, Masvingo, and Manicaland.

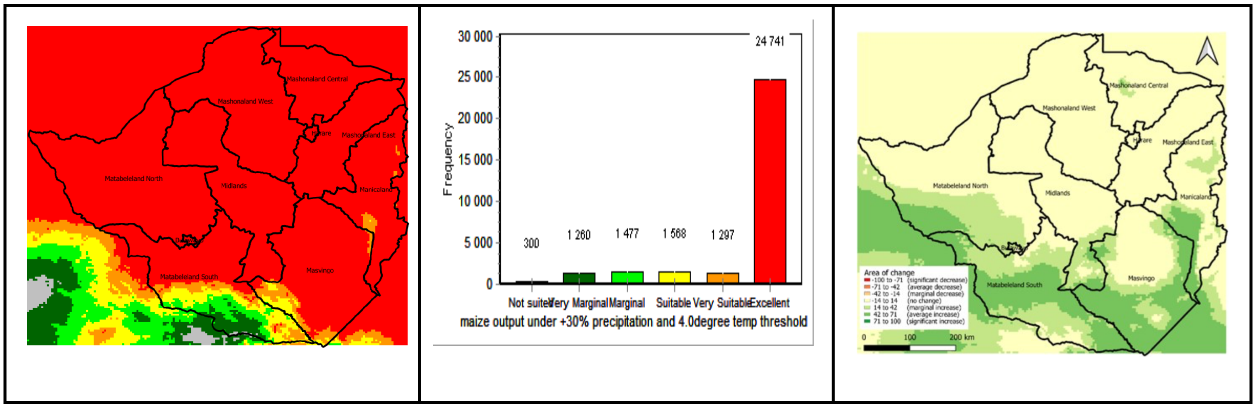


Figure 45 (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 4.0 °C increase combined with an increase in precipitation by 30%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 30% increase in precipitation and a 4.0 °C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 45a above shows the climate suitability for maize should temperatures increase by a 4°C increase accompanied by a 30% increase, although highly unlikely, in the average annual precipitation received in the country. Such climatic parameters are suitable for the cultivation of maize in some Provinces of the country. These climate conditions will be excellent in Provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, much of Matebeleland North, Masvingo, and Manicaland, and the extent of the area is larger than that of the historical patterns. Small parts of Manicaland, Masvingo, and Matabeleland North will, however, have some areas ranging from very marginal to very suitable, as shown by the frequencies in Figure 45b. Matebeleland South Province, however, despite the precipitation increase, will have other parts not being suited for maize growth. Figure 45c above shows the provinces that will likelyexperience a marginal to an average increase in suitability under a 4°C temperature increase and a30% increase in average annual precipitation. The areas that will change include Matebeleland North, South, Masvingo, and small parts of Midlands, Mashonaland Central, and Manicaland Provinces.

4.3.3.2. Tobacco

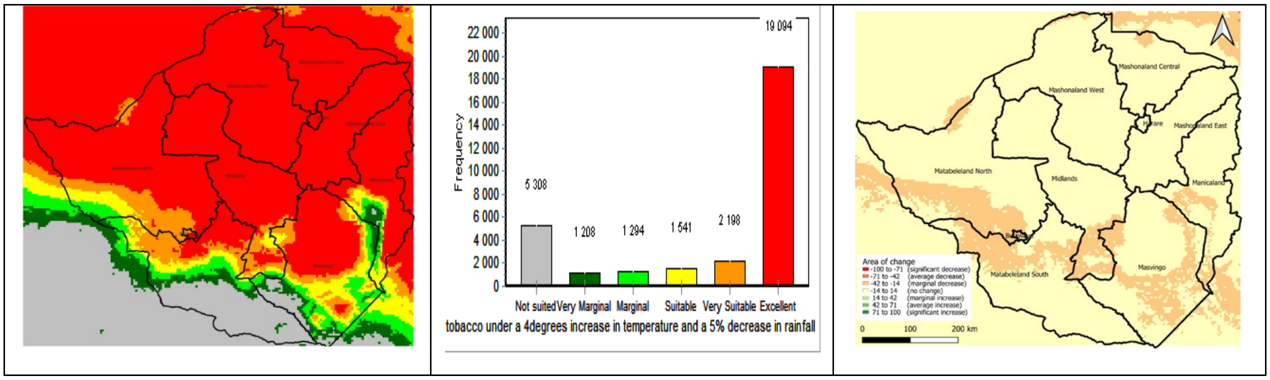


Figure 46 (left to right respectively). (a) shows the climate suitability for tobacco if temperature increases by 4°C combined with a decrease in precipitation by 5%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 5% decrease in precipitation and a 4°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Furthermore, if rainfall decreases by 5% of the average historical totals combined by 4°C, such climatic conditions indicate a marginal decrease in the areas suitable for tobacco, as shown in Figure 46a. When compared with the historical baseline, the **belt** in Figure 46a shows a slightly different pattern. The **belt** expands, moving northwards into the areas that were historically excellent in terms of suitability. When compared to the historical climate suitability patterns, Figure 46a above shows a slight decline in the areas suitable for the growth of tobacco. The extent of unsuitability will be marginal in Figure 46a covering most parts of Matebeleland South extending in Masvingo and small parts of Manicaland and Matabeleland North, and using frequencies shown on the histogram, see Figure 46b, the unsuitable areas increase. Areas that had climate suitable for tobacco during the period 1990-2018, when exposed to a 5% decrease in precipitation indicate a marginal decrease, as shown in Figure 46b. Figure 46c illustrates the areas that will experience change under a 5% decrease in rainfall compared to the historical patterns. The map shows that parts of Matabeleland North extending into Matebeleland South, Bulawayo, Midlands, Masvingo, and Manicaland will experience a marginal decrease in suitability.

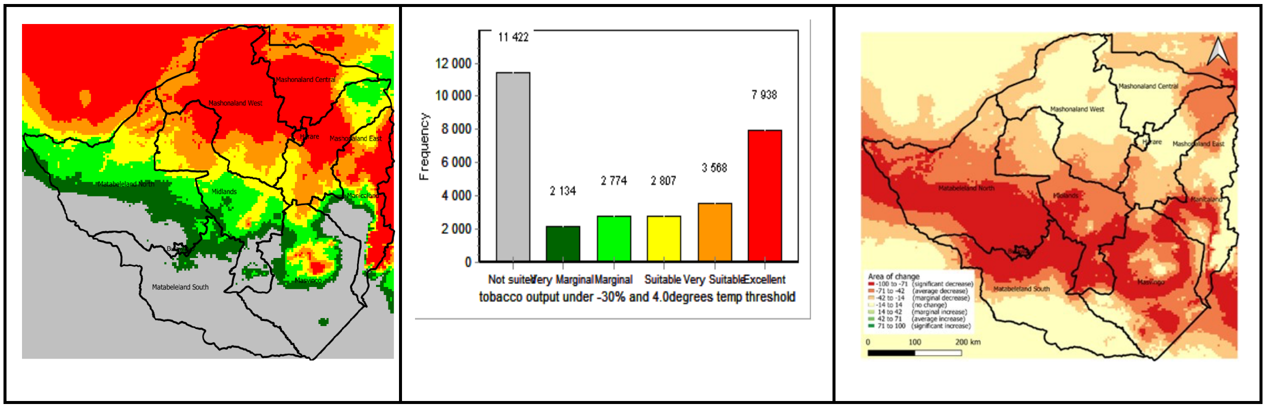


Figure 47 (left to right respectively). (a) shows the climate suitability for tobacco if temperature increases by 4°C combined with a decrease in precipitation by 30%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 30% decrease in precipitation and a 4°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 47a above shows the climate suitability for tobacco if temperatures increase by 4°C accompanied by a 30% decrease in annual average precipitation. Such climatic patterns show to be unsuitable for the cultivation of tobacco for commercial purposes. Historically 'excellent' in terms of suitability decrease in size only to cover Provinces such as Mashonaland West, Central, small parts of Mashonaland East, Manicaland, and Harare. Lower parts of the country, including Matebeleland South, Bulawayo, Masvingo; part of Matebeleland North, Midlands, and Manicaland provinces, will become unsuitable if such climatic patterns prevail. Other parts of these provinces will range from very marginal to very suitable. The map in Figure 47c shows the provinces that will likely change when compared to the historical output. The areas expected to experience a marginal to significant decrease include parts of Matebeleland North, Midlands, Mashonaland West, Mashonaland East, and Manicaland. Large parts of Matebeleland North extending into Matebeleland South, Bulawayo, Midlands, Masvingo, Manicaland, and a small part of Mashonaland Central will experience an average decrease in suitability in terms of climate.

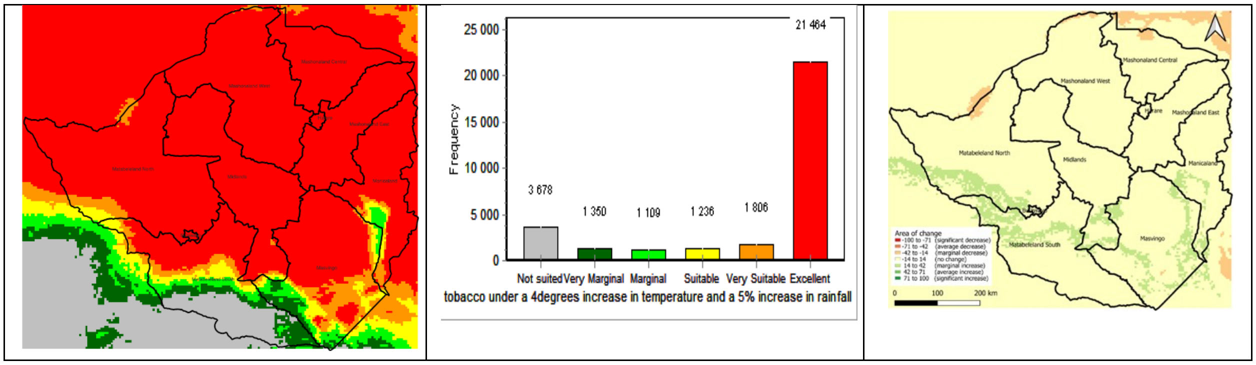


Figure 48 (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 4.0 °C increase combined with an increase in precipitation by 5%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 5% increase in precipitation and a 4°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Figure 48a above shows the climate suitability for tobacco if temperatures increase by 4°C accompanied by a 5% increase in the average annual precipitation received in the country. Based on the model's simulations, such climatic parameters are marginally suitable for the growth of tobacco in the country. These climate conditions will remain excellent in Provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, much of Matebeleland North, Masvingo, and Manicaland, and the area extent is larger than that of the historical patterns. The position of the **belt** extends southwards, resulting in a smaller part of the country becoming unsuitable for promoting the growing of tobacco, mainly Matabeleland South. Meanwhile, other parts of the country will experience a marginal increase in suitability under such climate conditions. This increase will be in small parts of provinces such as Bulawayo, Midlands, Matebeleland North and South, Masvingo, and Manicaland. Figure 48c (using the legend on *Insert 1* above) shows the areas in Zimbabwe likely to experience a marginal increase in suitability under the specified climatic patterns.

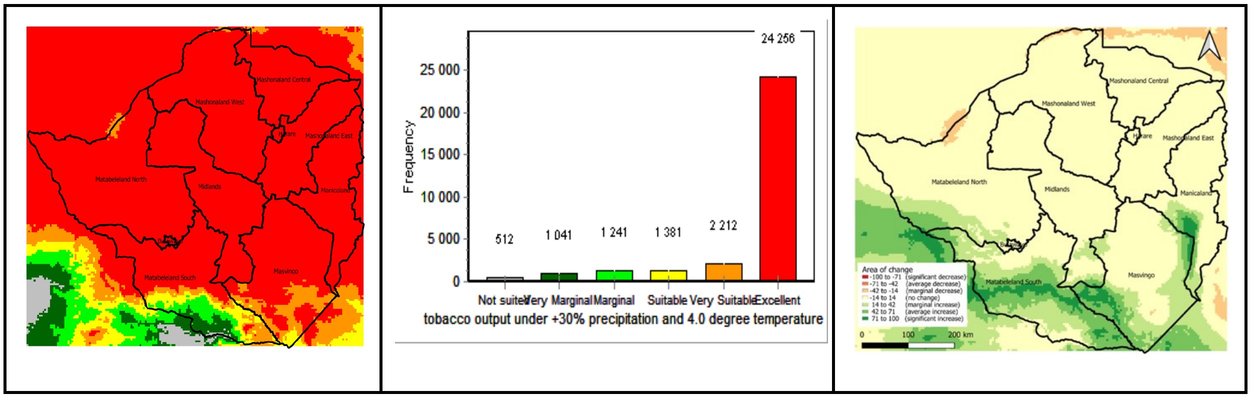


Figure 49 (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 4°C increase combined with an increase in precipitation by 30%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 30% increase in precipitation and a 4°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

Furthermore, Figure 49a above shows the climate suitability for tobacco if the annual precipitation increases by 30% and temperatures increase by 4°C. The models simulate that such climatic parameters are suitable for the growth of tobacco in the country. These climate conditions will be excellent in Provinces such as Bulawayo, Harare, Mashonaland East, West, Central, Midlands, much of Matebeleland North, Masvingo, and Manicaland, and their extent is larger than that of the historical patterns, and they could consequently improve the economic situation within thecountry. The frequency of this suitability increases significantly compared to the historicalpatterns, as shown in Figure 49b. The parts that will likely experience a marginal to a significant increase (see Figure 49c) when exposed to such climatic patterns include a small part of Matebeleland North, extending into Matebeleland South, Masvingo, and Manicaland. Small parts of Manicaland, Masvingo, and Matabeleland North will, however, have some areas ranging fromvery marginal to very suitable, as shown by the frequencies in Figure 49b. Matebeleland South province, however, despite the precipitation increase, will have other parts unsuited for tobacco cultivation.

Chapter 5: Discussion

This chapter shall discuss, interpret, and analyze the results presented in the previous chapter.

5.1 Sensitivity to temperature variations

5.1.1. Maize

Results from the previous chapter showed that when temperature averages increase by 2°C and historical annual rainfall remains fixed, the model simulations illustrate a marginal increase in suitability in smaller parts of maize-grown regions such as Mashonaland Central and parts of Manicaland Provinces, see Figure 8a. In other regions, when exposed to 2°C, they show no change even in regions known to be suitable; unsuitable areas remain unsuitable. The **belt** under historical climate patterns extends from the west to the south-east and follows the same pattern under a 2°C temperature increase. This simulation shows that a 2°C increase in temperature positively impact the suitability of maize in small parts of Zimbabwe.

When exposed to a 3°C and 4°C (see Figure 10a and 12a, respectively) temperature increase, the models also indicate a marginal increase in suitability in the maize-grown areas, Manicaland and Mashonaland Central. Makadho (1996) notes that higher temperatures promote the growth of crops whose phenology is influenced by temperatures, for example, maize. However, this reduces the length of the growing season, limiting the yield potential of the crop.

5.1.2. Tobacco

On the other hand, for tobacco, when temperature averages increase by 2°C and historical annual rainfall remains fixed, the model indicates that there will be no change in terms of suitability in the tobacco-grown areas of Zimbabwe. The historical **belt** that extends from the west to the south-east follows the same pattern. The extent of the **belt** will remain the same. Therefore, this simulation indicates that tobacco is less sensitive to a 2°C increase in average annual temperature.

Furthermore, for tobacco, when temperature averages increase by 3°C and historical annual rainfall remains fixed, the results indicate that there is likely to be no change when compared to the historical patterns. Under a 4°C temperature increase and historical annual rainfall remains fixed, the Ecocrop model indicates a marginal change in amplitude in terms of suitability in all the tobacco-grown areas of Zimbabwe. A marginal decrease in the northern parts of Mashonaland Central and Masvingo is observed, however, to the writer's knowledge, Masvingo is not a tobacco-grown area. Other regions exhibit no change in pattern; the historical **belt** follows the same pattern. Therefore, the model shows that tobacco is marginally sensitive to a 4°C increase in temperature, although at a low amplitude.

The Ecocrop model shows that an increase in temperature averages only does not translate to a decrease in yields, meaning that crops, maize, and tobacco, are little sensitive to temperature variations. However, one could argue that high temperatures can cause high evapotranspiration, thus affecting soil moisture content and eventually affecting plant growth. Although a 2°C and 4°C increase in temperature results in little sensitivity, it can be noted that the response of crops is non-linear. One could argue that there is a possibility of a 5°C increase in temperature to cause devastating effects on suitability.

5.2 Sensitivity to +/-5%, +/-15%, and +/-30% precipitation variations

5.2.1. Maize

Findings from the previous chapter indicate significant changes in climate suitability when varying precipitation averages are imposed on both maize and tobacco crops. If rainfall decreases by 5%, the results show that small areas previously known to be suitable for maize cultivation will likely experience a marginal decrease, as shown in Figure 14c above. This indicates that a 5% decrease in rainfall could potentially affect the suitability of maize very marginally, and the agricultural sectors will not be considerably affected in the maize-grown areas.

Furthermore, when precipitation **decreases** by 15% of the annual averages and historical temperatures remain fixed, results show that such climatic parameters negatively affect the suitability of maize in the country. The distribution of suitability patterns will change. A marginal to average decrease is observed in parts of Mashonaland East province, Figure 15c above, and this provincelie within the regions known as suitable for maize to date. The highly suitable will become marginal, and the marginal will become unsuited, see Figure 15a. A marginal to average decrease is also shown in areas of Midlands province, and parts of Masvingo province and these are already marginal, which means they will become very marginal, which could affect food security in the country.

If exposed to a 30% **decrease** in annual precipitation averages, the model projects that highly suitable areas will reduce into marginal and very marginal. Figure 16a shows that highly suitable areas will become just suitable, marginal, very marginal, and others not suitable. Figure 16c above shows that the country will experience a marginal to a significant decrease in areas previously known to be highly suitable for maize cultivation similarly to the projections noted by Mugabe et al, 2013. These areas include Mashonaland West, Mashonaland East, Mashonaland Central and, Manicaland Province, already marginal areas of Midlands and Masvingo will also experience a significant decline in suitability, as shown in Figure16c above. This change has a disastrous effect on the distribution of maize grown.

On the other hand, if the average annual precipitation **increases** by 5%, very small parts of the country will likely experience a marginal increase, as shown in Figure 20c above compared to the 15% and 30% increase outputs. This marginal increase is in parts of provinces previously known to be very marginal and unsuited, which could positively impact maize cultivation.

Meanwhile, under a 15% **increase** in rainfall (see Figure 21a above), the **belt** descends in a southward direction resulting in a marginal increase in suitability in areas previously known as unsuitable for maize cultivation. This **belt** covers agro-ecological regions 4 and 5, and these include Matabeleland North, Matabeleland South; southern parts of Midlands, Masvingo, and Manicaland, as illustrated in Figure 21c above. However, some areas in the southern part of the country will remain unsuited under a 15% increase, as shown in Figure 21a.

If precipitation **increases** by 30%, the results indicate a marginal to an average increase in suitability for the cultivation of maize. Under a 30% increase, highly suitable areas expand into very marginal and the unsuitable areas to become highly suitable, see Figure 22a above. The **belt** reduces in size, shifting to the southern part of the country, and previously unsuitable areas will likely become suitable. These areas include Matebeleland South parts of Matebeleland North, Midlands, Masvingo, and a small part of Manicaland.

5.2.2. Tobacco

Results from the previous chapter indicate that, when exposed to a 5% decrease in rainfall, a marginal decrease in suitability in smaller parts of the provinces previously known to be suitable for tobacco cultivation, that is Manicaland is observed, as shown in Figure 17c above.

Moving on, a 15% decrease in average annual rainfall has negative implications on the suitability of the climate for tobacco cultivation. The Ecocrop model projects both a marginal and average decrease in suitability, mostly in the regions of Manicaland, as shown in Figure 18c, and this area is known as tobacco growing areas which lie in agro-ecological regions 1 and 2. Highly suitable areas will become marginal to unsuited as compared with the historical pattern. The extent of the unsuitable area is smaller than that of a 30% decrease. However, some areas that will experience a decrease are not known to be suitable for tobacco.

Furthermore, under a 30% **decrease** in annual precipitation averages, a decrease in suitable areas, otherwise known as suitable historically, is likely to be observed, see Figure 19a above. The excellent regions will become marginal, and those that were marginal regions will become very marginal to unsuitable. Figure 19c shows this decrease in parts of Manicaland, Mashonaland West, and Mashonaland, and these provinces lie in agro-ecological regions 1 and 2, zones previously known as suitable for tobacco farming. The extent of the unsuitable areas will expand northwards into once highly suitable areas. This shows that tobacco is highly sensitive to changes in rainfall patterns compared to variations in temperature patterns.

However, if annual rainfall increases by 5%, a marginal **increase** in suitability for tobacco cultivation is likely to be observed. Regions previously known to be unsuited for the crop will also likely experience this marginal increase, including small parts of Matabeleland North and South, Masvingo, and Midlands, as illustrated in Figure 23c above. Compared to a 15% increase in rainfall, a 5% increase has very small areas likely to experience a marginal increase.

If annual rainfall averages are to increase by 15% (see Figure 24c) and historical temperatures remain fixed, these parameters are projected to positively affect tobacco suitability in areas previously known to be suitable. Provinces in the southern parts of the country (which lie in agro-ecological regions 4-5) currently known to be unsuited for tobacco cultivation are projected to experience a marginal to the average increase in suitability.

Furthermore, if precipitation **increases** by 30% and historical temperatures remain fixed (see Figure 25c), such climatic patterns prove to be suitable for tobacco cultivation. An expansion of highly suitable areas is shown even in areas currently unsuitable for tobacco cultivation. These include the lower parts of Matebeleland North, Matabeleland South, Midlands, Masvingo, and Manicaland, provinces which lie in agro-ecological regions 4 and 5. The **belt** in both Figure 24a and 25a (in chapter 4) descends into the southern parts of the country, parts previously known as unsuitable for tobacco in terms of climate and other factors.

5.3. Sensitivity to a combination of temperature and precipitation variations

Results from the previous chapter also presented simulations of climate suitability when increased average temperatures are combined with either increased or decreased annual precipitation averages.

5.3.1. Maize

Findings show that if a 5% **decrease** in rainfall is combined with 2^{o}C, 3^{o}C, and 4^{o}C increase in temperature, a slightly marginal decrease will likely be observed. The marginal decrease is projected to be in small parts of provinces that lie in agro-ecological regions 3-5, which are already marginal areas. Therefore, a combination of a 5% decrease in precipitation and a 2^{o}C, 3^{o}C, and 4^{o}C increase in temperature can hardly be accounted for as it will not affect the usual maize cultivation patterns.

Meanwhile, when a 2^{o}C, 3^{o}C, and 4^{o}C temperature increase is combined with a 15% **decrease** in annual average rainfall amount, a marginal to an average decrease in suitability in areas previously characterized as suitable and unsuitable. Highly suitable regions will likely become marginal, very marginal, and others unsuited (see Appendix A, B, C, below). These areas include provinces which lie in agro-ecological regions 1 and 2, that is, Mashonaland Central, Mashonaland West, Mashonaland East, Harare, and Manicaland. The **belt** shifts and expands northwards into once highly suitable areas. A decrease in already marginal areas of Masvingo and Midlands, which lie in agro- ecological region 3, is also observed as these marginal areas will become very marginal. This means that such climatic parameters can be a cause for concern to both smallholder and large-scalemaize cultivation and strategists as they could lead to food insecurity and thereby affecting the standards of living in the country.

When the 2^{o}C, 3^{o}C, and 4^{o}C temperature increase is combined with a 30% **decrease** in annual rainfall averages, the result in maize distribution could be disastrous (see Figures 27a, 35a, 43a, respectively, Chapter 4). This is because a significant decrease in maize-grown areas is projected. Highly suitable areas will likely become marginal, very marginal, and others unsuited. These areas include provinces that lie within agro-ecological regions 1 and 2, that is, Mashonaland Central, Mashonaland West, Mashonaland East, Harare, and Manicaland, and these are regions currently known as suitable. The **belt** shifts and expands northwards into once highly suitable areas. A decrease in already marginal areas of Masvingo and Midlands, which lie in agro-ecological region 3, is also observed as these marginal areas will become very marginal. This climatic pattern is almost similar to drought-like conditions, and crops such as maize will not be able to thrive. However, under these climate conditions, small parts of Mashonaland Central and Manicaland provinces indicate a slight increase in suitability for maize. This decrease will put a strain on the country's food security. For the country to face this challenge, there is a need to draw policies that facilitateand encourage irrigation schemes and introduce drought-resistant maize crop varieties.

On the other hand, a very sparse marginal increase is projected if a 2^{o}C, 3^{o}C, and 4^{o}C temperature increase are combined with a 5% **increase** in annual average precipitation. The projected minor marginal increase is to be experienced in the formerly unsuitable agro-ecological regions; therefore, this change can be a step toward improving food security in the country. The observations also further support that the maize crop is less sensitive to increasing temperature variation compared to varying precipitation averages.

Furthermore, if a 2^{o}C, 3^{o}C, and 4^{o}C temperature increase are combined with a 15% increase in annual average precipitation, a marginal increase in suitability in maize-grown areas will likely be observed. Highly suitable areas will expand in size into previously marginal and very marginal agro-ecological regions 4 and 5, and the **belt** will recede into the southern part of the country.

Unsuitable areas will shift, with just a smaller part of the country remaining unsuitable for maize (see Appendix A, B, and C below). Agro-ecological regions 1-3 will remain highly suitable for maize in the northern and western parts of the country.

A significant increase in suitability in maize-grown areas is also observed when a 2^{o}C, 3^{o}C, and 4^{o}C temperature increase is combined with a 30% **increase** in annual average rainfall. Excellent areas in terms of suitability will expand into agro-ecological regions previously known as marginal regions, that are, regions 4 and 5. Marginal areas of Midlands and Masvingo Province indicate a significant increase according to the Ecocrop simulations in Figures 29c, 37c, and 45c (see Chapter 4). The **belt** will reduce to the southern part of the country, almost eliminating unsuitable areas. Such responses of maize to the change in climate will likely impose a positive impact on the country's food security.

5.3.2. Tobacco

A slight marginal decrease is likely to be observed under a 5% **decrease** in rainfall combined with varying temperature levels, see Figures 30c, 38c, and 46c in Chapter 4 above. However, this decrease is mostly in areas already classified as unsuited to date. A decrease in already marginal areas of Masvingo and Midlands, which lie in agro-ecological region 3, is also observed as these marginal areas will become very marginal.

In addition, when a 2^{o}C, 3^{o}C, and 4^{o}C temperature increases is combined with a 15% **decrease** in annual average rainfall amount, a marginal to an average decrease in suitability in areas previously characterized as unsuited. Highly suitable areas will likely become marginal, very marginal, and others unsuited, see Appendix below. Tobacco is a cash crop that significantly contributes to Zimbabwe's GDP, and such climatic conditions should drive the country to develop adaptation and mitigation measures to ensure that the crop continues to thrive.

Furthermore, a combination of 2^{o}C, 3^{o}C, and 4^{o}C temperature increase and a 30% **decrease** in annual average precipitation prove to have tremendous effects on the suitability of the tobacco crop. Highly suitable areas will reduce in size as unsuitable areas expand northwards. Figure 28c, A2.6c, and 38c (see chapter 4 and Appendix below) indicate a decrease in suitability in lower parts of Manicaland, parts of Mashonaland West, and Mashonaland East, and these are known as tobacco-grown areas historically. The **belt**, consisting of very marginal to very suitable margins, will shift, expanding to the northern parts of the country. Northern parts of Mashonaland Central, East, and smaller part of Manicaland will change from being excellent in terms of suitability to become only suitable and marginal. Generally, yields decline when the amount of annual rainfall decrease. These results further purport that the two crops under study, maize, and tobacco, are more sensitive to precipitation variations than temperature variations only.

If 2^{o}C, 3^{o}C, and 4^{o}C temperature increases are combined with a 5% **increase** in annual average precipitation, a very sparse marginal increase is projected. The projected minor marginal increase is to be experienced in the formerly unsuitable agro-ecological regions; therefore, this change can be a step toward improving the economic situation of Zimbabwe as tobacco is a major export crop. The observations also further support that tobacco is less sensitive to increasing temperature variation than varying precipitation averages.

Moreover, if a 15% increase in precipitation is combined with temperature variations of 2^{o}C, 3^{o}C, and 4^{o}C, there is an expansion in the size of excellent regions. The highly suitable areas, however, are in agro-ecological regions that do not promote the growth of tobacco, that is, regions 3 to 5. The **belt** lowers into the southern parts of the country resulting in the unsuitable, very marginal, and marginal areas reducing in size, although a part of Matabeleland South will remain unsuitable. Tobacco, also known as the ‘golden leaf’, is an important export commodity in Zimbabwe. It has been generating foreign revenue annually, and it directly employs a significant number of people. Therefore, determining the sensitivity of the crop will not only benefit the economy but also better people’s livelihoods.

On the other hand, when increased temperature variations of 2^{o}C, 3^{o}C, and 4^{o}C are combined with increased annual precipitation averages by 30%, although improbable, an increase in suitability for tobacco is observed. Regions previously known as unsuitable as simulated by the Ecocrop model will increase in suitability. The extent of highly suitable areas will expand to the northern parts of the country, and the **belt** will shift, simultaneously reducing in size to the southern part of the country. The regions that will increase in suitability include the lower parts of Matebeleland North, Matabeleland South, Midlands, Masvingo, and Manicaland, the provinces within the agro-ecological Regions 4 and 5, regions known to be unsuitable for tobacco according to the writer's knowledge.

Table 4. Summary of the results discussed

		Precipitation changes						
		-5%	-15 %	-30%	Historical	5%	15%	30%
	historical	Result section 4.2			historical baseline in Materials and Methods	Result section 4.2		
temperatur echanges	2^{o}**C**	Results section 4.3- the pattern shows a decrease in suitability from the west and south-eastern part expanding northwards into areas previously known as suitable for both crops.			Result section 4.1	Results section 4.3- these climate conditions shows that suitability increases into the southern part of the country, areas previously known as unsuited.		
	3^{o}C							
	4^{o}**C**							

5.4. Maize and tobacco responses under independent temperature, rainfall change and under combined variations.

The results show that the crops under study, maize, and tobacco, are more sensitive to precipitation variations than temperatures variations only. This is because when precipitation averages vary, significant changes in climate suitable for maize and tobacco cultivation are observed even in areas currently known as unsuitable. With decreased rainfall averages, there is low suitability, and with increased averages, there is high suitability. In support of this observation, in a study conducted by Jerie and Ndabaringi (2011) on the impacts of rainfall variability on rainfed tobacco in the Manicaland Province of Zimbabwe, the results illustrated that despite other factors, rainfall variability is a significant factor influencing the decline in yields in this Province. Thus, rainfall variability directly affects tobacco output in the country. A decrease in rainfall directly translates to a reduction in yields and vice versa, Jerie and Ndabaringi (2011).

Under the independent temperature changes, the suitability of maize marginally increases in very small parts of maize-grown areas of Manicaland and Mashonaland Central. Meanwhile, if tobacco is subjected to 2^{o}C and 3^{o}C temperature increases, its suitability does not change, and under 4^{o}C temperature increase, there is a marginal decrease in areas known as unsuited for tobacco cultivation. This further purport that both crops are less sensitive to the varying temperatures, and therefore the staple crop (maize) and cash crop (tobacco) could thrive under such conditions.

Furthermore, under a combination of increasing temperatures and varying precipitation, the suitability of both crops changes as different precipitation parameters are imposed. Additionally, the results show that precipitation plays a significant role in determining the suitability of the two crops under study.

Chemara et al., (2013) assessed the impact of climate change on the suitability of rainfed flue-cured tobacco (Nocitiana tobacum L.) in Zimbabwe. Results validated that precipitation-related factors are the most important variables affecting the tobacco cultivation in Zimbabwe. The study also identified that Mashonaland West, Central, East, and Manicaland provinces, that is, agro-ecological regions 1 and 2, are suitable areas for cultivation because of the annual average rainfall received in these areas. Additionally, Newsham et al., (2021) note that, the projected erratic rainfall will likely make it difficult to cultivate tobacco and in some areas the progressive change in climate has resulted in the crop not being cultivated. Not only tobacco, but earlier studies have also shown strong links betweenrainfall and maize yield outputs in Zimbabwe (Richardson, 2007). In addition, the World Meteorological Organization (WMO) report on Zimbabwe (2007) concluded that, “rainfall is by far the most important variable that affects crop production.”.

Plants are directly affected by an increase in temperature through heat waves, and this impact will be doubled, especially when the increasing temperatures are coupled with low rainfall patterns, which directly affect soil moisture. In the earliest study by Hussien (1987), results suggested that in Zimbabwe, crop production is determined by rainfall, with temperature not being a limiting factor. However, a combination of high temperature and low rainfall will certainly reduce suitability, as was shown by the findings in Chapter 4.

Chapter 6: Conclusion and Recommendations

The objectives of this study were; to investigate the spatial suitability of maize and tobacco under historical average conditions in Zimbabwe; to perform a spatial analysis of suitability resulting from increased average temperature levels of 2°C, 3°C, and 4°C; to perform a spatial analysis of suitability resulting from a 5%, 15%, and 30% decrease and 5%, 15%, and 30% increase in the annual average rainfall patterns; and to spatially analyze the resulting suitability sensitivity to the combined variation of temperature and rainfall. Temperature levels 2°C, 3°C, and 4°C were used because they fall within the future projected temperature increase margins because of climate change in Zimbabwe. Also, due to uncertainties in climate change projections, both an increase and decrease in rainfall averages were used in this assessment.

6.1. Key findings

Findings revealed that a 5%, 15%, and 30% decrease in historical average rainfall negatively correlates with the climate suitable for both maize and tobacco. A decrease in rainfall leads to a decrease in suitability. Highly suitable areas will shift to become marginal, very marginal, and other parts unsuitable. An increase in precipitation also translated to an increase in suitability. Formerly marginal areas will become highly suitable, and unsuitable regions will reduce in size and range from very suitable to very marginal. The study showed that the crops under study are highly responsive to changes in precipitation. Therefore, with high confidence, the writer can conclude that the study demonstrates a strong influence of rainfall on the suitability of both maize and tobacco.

A spatial analysis of suitability resulting from increased temperature levels was performed for both tobacco and maize. Results showed that both the crops are a little sensitive to variations in temperature averages. Agro-ecological regions suitable for maize cultivation will experience a very minor increase in suitability under 2°C, 3°C, and 4°C temperatures change. On the other hand, under a 2°C, 3°C temperature change, tobacco will experience no change in suitability when compared with the historical baseline. Under a 4°C temperature level, the crop will experience a slight decrease in suitability; however, this decrease is shown in the agro-ecological region not known to be suitable for tobacco cultivation.

An analysis of suitability resulting from a combination of increased temperature levels and variations in average rainfall amounts was performed. The study showed that when increasing temperatures are coupled with low rainfall patterns, a decline in suitability is to be expected for both maize and tobacco. A significant part of highly suitable areas will shift to marginal and others completely unsuitable, especially for maize, yet it is an essential crop in the country. Whereas, when increasing temperatures are combined with high rainfall patterns, suitability will increase, and even previously unsuitable areas will shift to range between very suitable to very marginal.

6.2. Key lessons

This research aimed to analyze the sensitivity of maize and tobacco crop suitability in Zimbabwe in response to changes in temperature and rainfall patterns. Results from this study show a significant decline in the areas suitable for maize and tobacco in response to climate change. If rainfall decreases by 5%, 15%, and 30% of the historical averages, these climatic patterns prove unsuitable for both maize and tobacco. This is because the Ecocrop model shows a decline in the regions that were previously known as suitable in agro-ecological zones from 1-3. These areas include, Mashonaland Central, Mashonaland West, Mashonaland East, Harare, and Manicaland, and parts of these zones will become marginal, very marginal and others unsuitable. The same applies to tobacco; when exposed to a 5%, 15%, and 30% decrease in rainfall averages, the agro-ecological zones previously known as suitable will reduce in size, and others becoming marginal. These regions include Manicaland, Mashonaland Central, Mashonaland West, and East provinces.

Moreover, an increase in temperature by 2°C, 3°C, and 4°C combined with a decrease in rainfall averages by 5%, 15%, and 30% resulted in a marginal to a significant change in suitability for both maize and tobacco. Areas in agro-ecological zones best known for both crops will change from being excellent in terms of suitability to marginal and others unsuitable under these climatic parameters. Implications of climate change can be disastrous, leading to a decline in maize which would affect food security, and a decline in tobacco outputs would affect the country's economy. These projections will likely increase the vulnerability of both farmers and consumers; therefore, specific adaptation and mitigation strategies need to be implemented.

Globally, temperature increases have been noted and are leading to changes in rainfall amount, which could affect crop production (Weber, 2010). Evidence of increased global temperatures has been noted; these will lead to changes in the amount of rainfall received, significantly affecting crop production. High temperatures and low precipitation may reduce crop outputs due to water deficit owing to dry spells coupled with poor timing of the start of the growing season.

Furthermore, when comparing the two climate variables, rainfall, and temperature, with high confidence, the writer can conclude that the study demonstrates a strong influence of rainfall on the suitability of both maize and tobacco. The model illustrated that when varying rainfall amounts are imposed onto the crops, significant changes in suitability can be noted, unlike for temperature variations only. Thus, in summation, both maize and tobacco are heavily dependent on rainfall availability, and because of the projected climate change pattern, it is essential to draw other options to ensure a sufficient supply of the crops.

6.3 Recommendations

Uncertainties in climate change projections could make it challenging to recommend accurate responses through policies and strategies. Despite these challenges, however, priority can be given to sustainable growth of agricultural production systems, for example, crop diversification. For instance, if precipitation decreases by 30% of the annual average, new crop varieties could be introduced in the agricultural sector, in particular, the drought-resistant crops as well early maturity maize and tobacco crops in the event of shortened length of the growing season as well as the promotion of irrigation infrastructure to mitigate water scarcity.

Mano and Nhemachema (2007) also suggest that the Zimbabwean government could invest in the meteorological department, research and together with non-governmental organizations (NGOs) and the private sector. This is because they could provide adequate information services to ensure that farmers receive updated information on rainfall patterns for the coming seasons and early-warning systems so that they can make informed decisions on the planting dates. Additionally, policymakers could devise and implement policies and programs that meet farmers' needs to adapt or mitigate climate change, for example, climate smart-agricultural policies (Tirivangasi and Nyahunda, 2019).

Anticipatory measures can also be considered when addressing the likely impacts of climate change. Smallholder farmers' performance can be improved through increasing training. These come from promoting awareness about the magnitude of climate change and livelihood diversification, especially to smallholder farmers. There is also a need for the government to improve the accessibility of agricultural resources such as fertilizers and seeds before the start of the next growing season (Mano and Nhemachena, 2007). These farmers play a significant part in the total output of yields in Zimbabwe; therefore, should the suitability of the crops change, they must be aware of how to prevent food shortages and, inevitably poverty.

Other long-term measures will alleviate climate change effects. These measures could include maximizing outputs of both crops in the areas that have shown to remain suitable under 4°C temperature increase and a 30% decrease in rainfall. This can also be achieved through intensifying technological advancements such as rainwater harvesting (Chanza, 2018) and cloud seeding, among others. Appropriate farm technologies and management practices will improve the chances for sustainable adaptation to the threatened crops. In the long run, reducing greenhouse gases could limit climate change impacts.

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APPENDICES

APPENDIX A

Spatial analysis of suitability sensitivity resulting from a combination of +/-15%precipitation and a 2°C temperature increase.

Maize

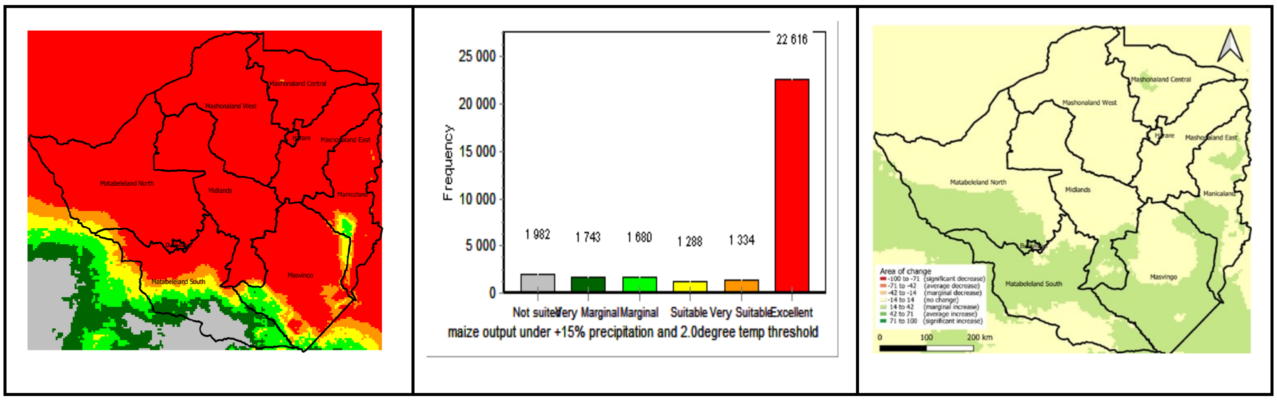

Figure A1.1. (left to right respectively). (a) shows the climate suitability of maize if temperature increases by a 2°C combined with an increase in rainfall by 15%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 15% increase in rainfall and a 2°C temperature increase. (c) shows areas of change when compared to the historical outputs.

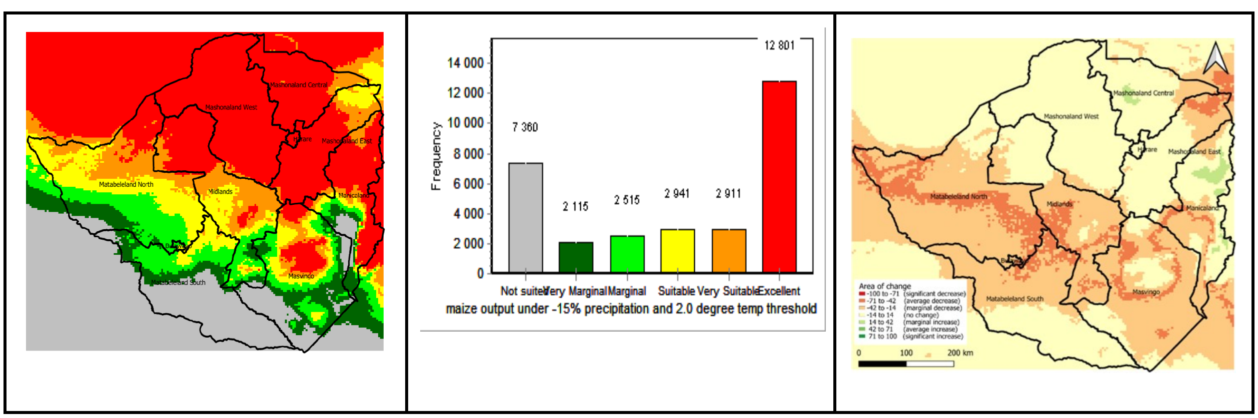

Figure A1.2. (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 2°C combined with a decrease in precipitation by 15%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 15% decrease in rainfall and a 2°C temperature increase. (c) shows areas of change when compared to the historical outputs.

Tobacco

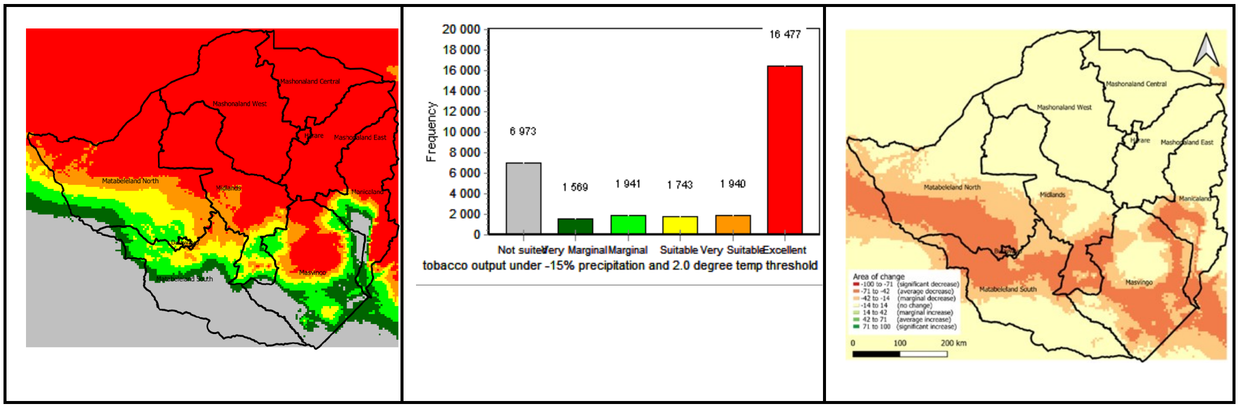

Figure A1.3 (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 2°C combined with a decrease in precipitation by 15%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 15% decrease in precipitation and a 2°C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

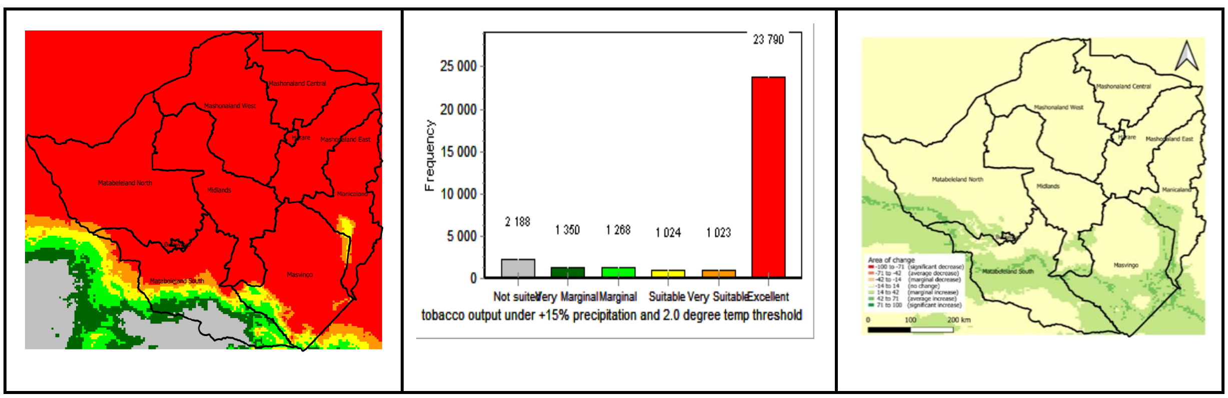

Figure A1.4 (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by a 2.0 °C increase combined with an increase in precipitation by 15%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 15% increase in precipitation and a 2.0 °C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

APPENDIX B

Spatial analysis of suitability sensitivity resulting from a combination of +/-15% precipitation and a 3°C temperature increase.

Maize

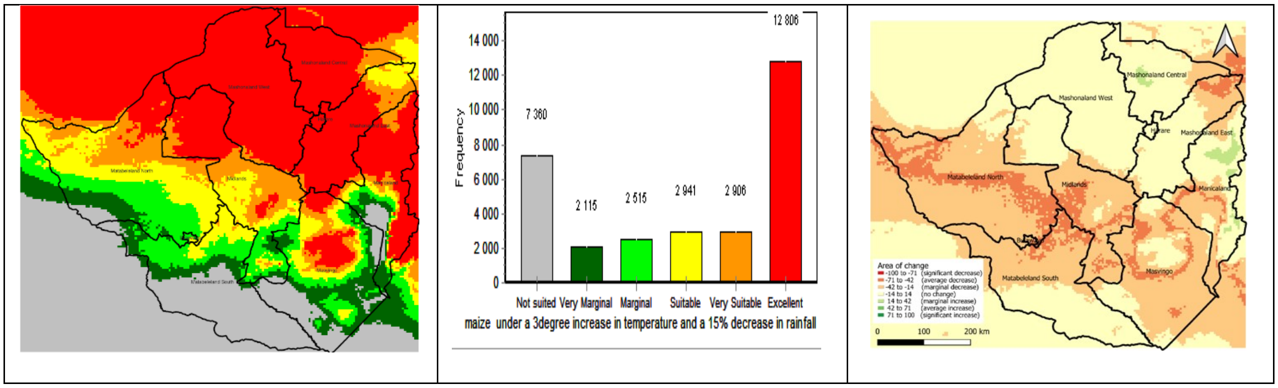

Figure B1.1 (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 3 °C combined with an decrease in precipitation by 15%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 15% decrease in precipitation and a 3°C temperature increase. (c) shows areas of change when compared to the historical outputs.

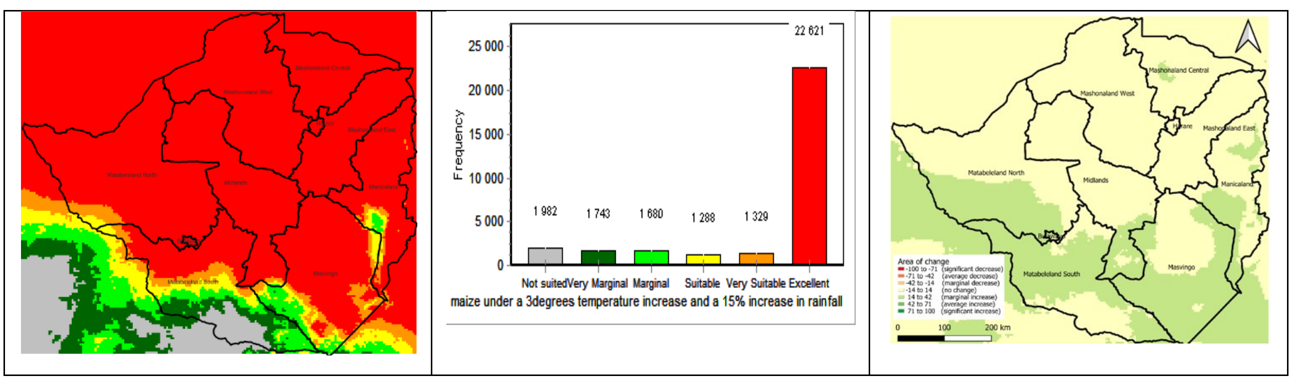

Figure B1.2. (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 3 °C combined with an increase in rainfall by 15%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 15% increase in rainfall and a 3°C temperature increase *(c) shows areas of change when compared to the historical outputs*.

Tobacco

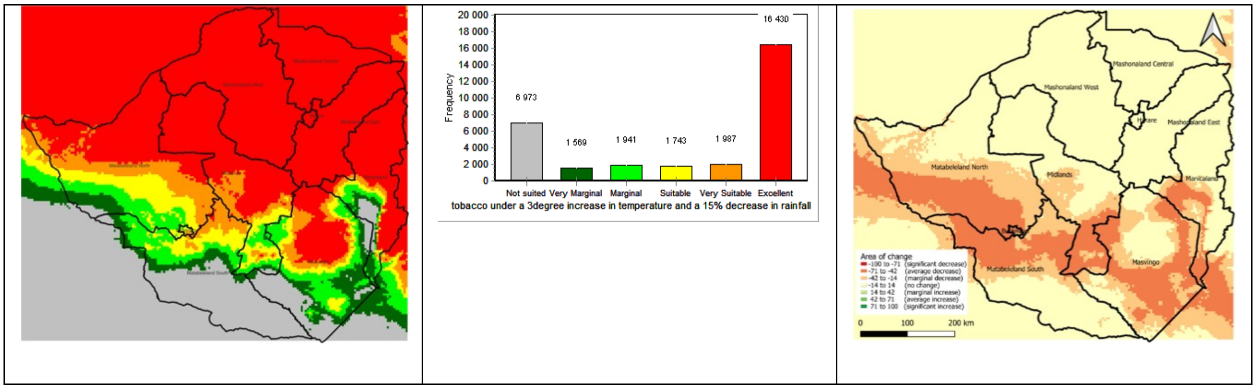

Figure B1.3. (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 3°C combined with an decrease in precipitation by 15%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 15% increase in precipitation and a 3°C temperature increase. (c) shows areas of change when compared to the historical outputs.

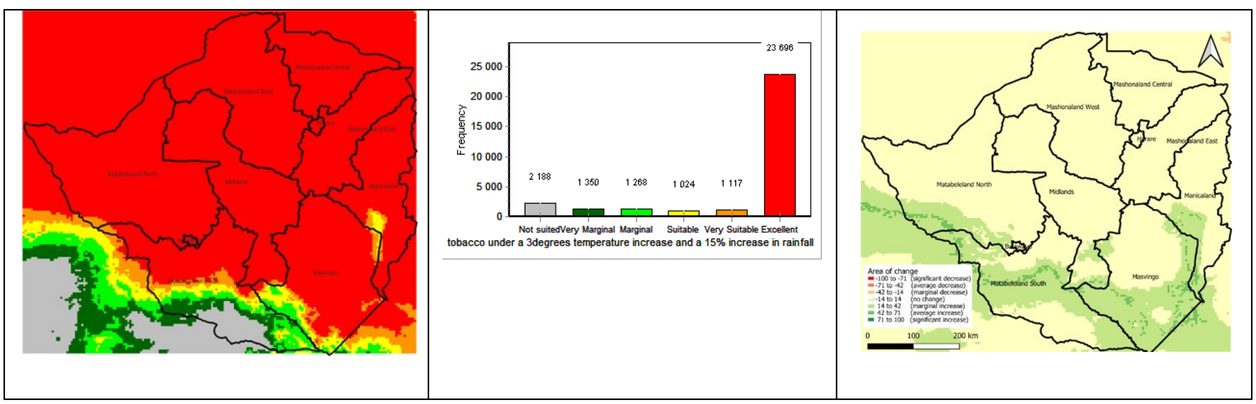

Figure B1.4. (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 3°C increase combined with an increase in rainfall by 15%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 15% increase in rainfall and a 3°C temperature increase. (c) shows areas of change when compared to the historical outputs.

APPENDIX C

Spatial analysis of suitability sensitivity resulting from a combination of +/-15% precipitation and a 4°C temperature increase.

Maize

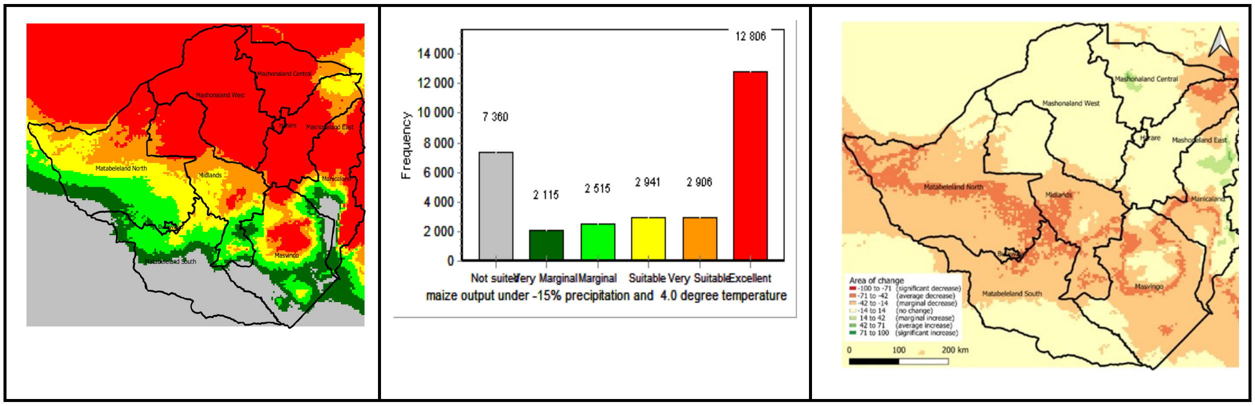

Figure C1.1 (left to right respectively). (a) shows the climate suitability of maize if temperature increases by 4.0 °C combined with a decrease in precipitation by 15%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 15% decrease in precipitation and a 4 °C temperature increase. (c) shows areas and amplitude of change as a spatial result of variant climate minus baseline climate.

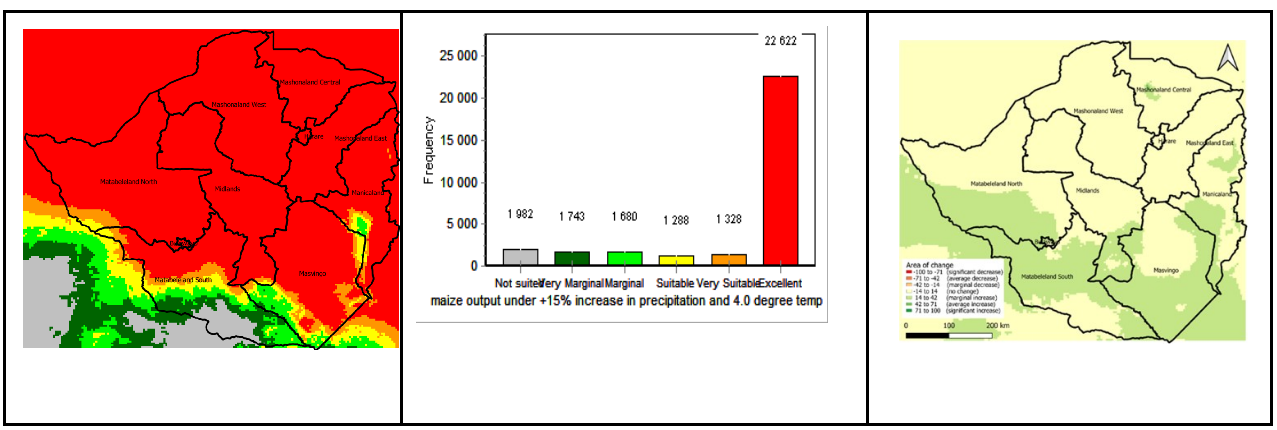

Figure C1.2. (left to right respectively). (a) shows the climate suitability for maize if temperature increases by 4.0 °C combined with an increase in precipitation by 15%, (b) histogram representing the frequencies and distribution of climate suitability for maize under a combination of a 15% increase in precipitation and a 4°C temperature increase. (c) shows areas of change when compared to the historical outputs.

Tobacco

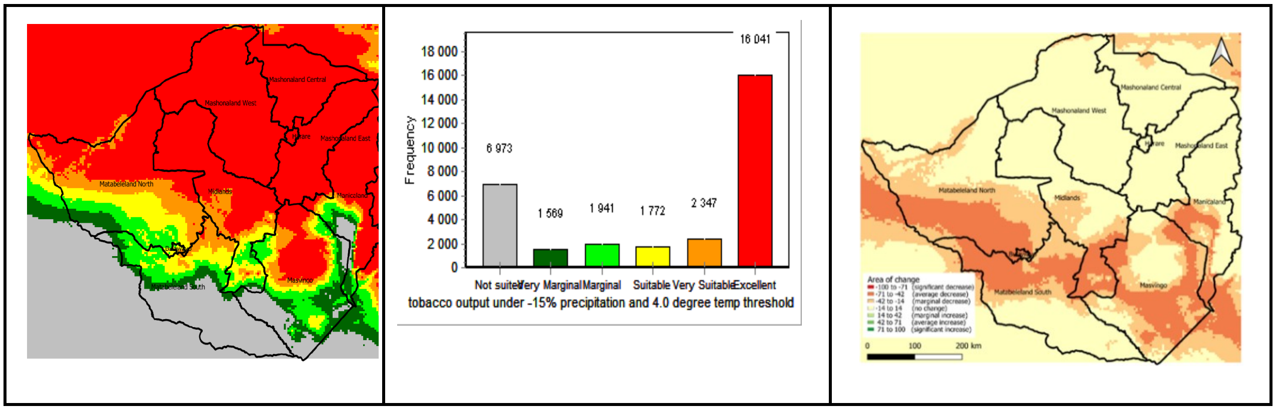

Figure C1.3. (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 4.0 °C combined with a decrease in precipitation by 15%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 15% decrease in precipitation and a 4.0 °C temperature increase. (c) shows areas of change when compared to the historical outputs.

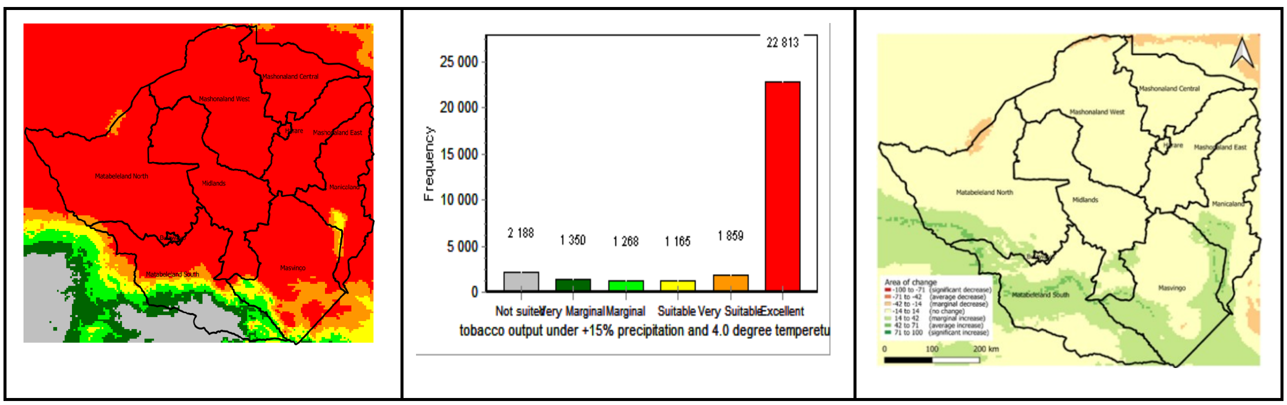

Figure C1.4. (left to right respectively). (a) shows the climate suitability of tobacco if temperature increases by 4.0 °C increase combined with an increase in precipitation by 15%, (b) histogram representing the frequencies and distribution of climate suitability for tobacco under a combination of a 15% increase in precipitation and a 4.0 °C temperature increase. (c) shows areas of change when compared to the historical outputs.