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Climate change effects on the sub-Saharan agriculture- a case study in Kenya on maize growth and adaptation options

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Climate change effects on the sub-Saharan agriculture- a case study in Kenya on maize growth and adaptation options

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Master thesis, 30 credits, in *Physical Geography and Ecosystem Analysis*

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Abstract

Climate change is progressively advancing, and is affecting the entire globe, with some areas more vulnerable than others. Among them, the sub-Saharan Africa, with a very low adaptive capacity, mainly relies on one economic sector: agriculture. Due to its high climate-dependency, agriculture is at elevated risk. In this frame, models are essential for the projection of future climate change scenarios, and for the development of adaptation strategies, fundamental to tackle the adversities induced by climate change. Maize is the most produced staple crop in the sub-Saharan Africa, and partly guarantees food security. However, climate change is projected to lower maize yields, negatively affecting an entire region which already suffers high levels of famine. In this study, two maize varieties based on their sowing date, early and late, are modelled under the RCP8.5 scenario using climate data retrieved from CORDEX for temperature, precipitation and evapotranspiration, from 1951 to 2100. The simulations are set in three sites in Kenya with diverse climate conditions, soil profiles and biomes. Early and late maize yields and biomass was simulated using the crop model AquaCrop, developed by FAO. In parallel, important temperature-dependent maize development thresholds was specifically analyzed. The results indicated lower early maize biomass and yields in a future climate change scenario. Furthermore, the limitation of AquaCrop of only simulating year-by-year was discussed. It is therefore suggested to run model simulations on a longer time span in order to better project future climate change impacts. In addition, the late sowing maize variety resulted the most suitable option for adaptation, able to guarantee sufficient yield amounts. This study can contribute to the work of assessing climate change derived social implications in the sub-Saharan Africa, such as future food security and migrations.

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Abbreviations

CCC: Canadian Center for Climate

CORDEX: Coordinated Regional Climate Downscaling Experiment

DOY: day of the year

GCM: General Circulation Model

GDD: growing degree-days

GM: genetically modified

ETo: evapotranspiration

LCLUC: land cover and land use change

RCA4: Rossby Centre Regional Atmospheric Climate Model

RCM: regional climate model

SMHI: Swedish Meteorological and Hydrological Institute

SSA: sub-Saharan Africa

1. Introduction

1.1 Climate change

Climate change has progressively gained attention in the past decades. It is challenging to explain what it actually is since many levels need to be considered. It is triggered by both natural and human forcings as reported by the IPCC (Cubasch et al., 2013). Certainly, the Earth is subjected to natural variations that occur on different temporal and spatial scales (Cubasch et al., 2013). However, currently a very relevant part of alterations is induced by human actions that modify the Planet's energy budget. Concretely, it is caused by changes in emissions of gases such CO_2, CH_4 and N_2O and aerosols, which in turn, result in different atmospheric concentrations, therefore leading to imbalances on different levels (Cubasch et al., 2013). Solar radiation plays a significant role in regulating the Earth's climate. There is a radiative balance between incoming solar shortwave radiation and outgoing longwave radiation. If altered, it is usually by natural fluctuations of solar cycles, which modify the incoming shortwave radiation. However, human actions have progressively started contributing to the alteration of the radiative balance. Another relevant aspect in terms of alterations is related to surface albedo. It is defined as the fraction of solar radiation reflected by a surface or object (IPCC, 2013). Therefore, changes in vegetation or land surface properties can modify the surface albedo. They can be either natural or human induced. For instance, seasonal changes are responsible for snow disappearance, thus resulting in lower albedo (natural induced). An example for the human induced is represented by deforestation, which results in vegetation loss, leading to a higher albedo (Cubasch et al., 2013).

Two concepts are also relevant while considering climate change and human actions; land cover, defined as the biophysical aspects of the Globe's surface, and land use, which is purpose for which humans use the land (Hu et al., 2019). Human activities are leading to continuous modifications of land through two alteration actions. When the modification affects the categorical properties, it takes the name of land use change or land cover conversion (Hu et al., 2019). A concrete example for land use change is forestry to cropping, while for land cover conversion is from forest to grassland. When the modification touches the actual properties of land, it takes the name of land use intensity change and land cover modification. Respectively, an example is the change in intensity of treatment for a cropland (from strong to weak thinning), and for land cover modification is from an intact to a degraded forest (Hu et al., 2019). These modifications certainly affect the Earth's energy balance, without considering all the different impacts that they can have, from a global to a local scale, in long and short terms. However, what is also important to know in this frame is that, even though it is happening on a global scale, some areas result more vulnerable than others (Niang et al., 2014). Therefore, this factor rises a relevant concern, especially when it affects countries that are not sufficient in terms of development and economic growth. Among the different ones, the sub-Saharan Africa has been reported as one of the most affected areas by the climate change impacts (Serdeczny et al., 2016).

1.2 Future climate projections over Africa

Observations have shown an average surface temperature increase (0.5°C or more) in the African continent over the past 50 years (Niang et al., 2014). Over the coming century, future trends project some of the fastest temperature increase in Africa (Niang et al., 2014; Serdeczny et al., 2016). Under the RCP8.5, the average annual temperature is projected to increase by 2°C or more in most African land areas until mid-21st century, and by 4°C or more by the end of the century (Niang et al., 2014). In respect to precipitation, the absence of observational data for many African areas and, if present, their discrepancies, represent a relevant constraint. However, for the areas whose rainfall data is sufficiently provided, annual precipitation decreases have been observed in the eastern and western Sahel region in northern Africa over the past century. Increases have been registered in eastern and southern Africa (Niang et al., 2014). In respect to future rainfall trends, the CMIP5 (Coupled Model Intercomparison Project Phase 5) showed an intervariability of scenarios for the different areas of the continent. Under the RCP8.5, decreases in the average annual precipitation will be very likely in the Mediterranean region of northern Africa and in southern Africa for the mid and late (excluding South Africa, which will show slight precipitation increases) 21st century. Differently, in central and eastern Africa increases in mean annual precipitation are projected during mid-century (RCP8.5) (Niang et al., 2014).

Climate change, whether induced by natural or human forcings, can modify the occurrence or intensity of extreme weather and climate events, or both (Cubasch et al., 2013). The African continent, depending on the geographical area, is extremely subjected to climate extremes such as heatwaves, floods and droughts, whose frequency and strength have been enhanced by climate change (Serdeczny et al., 2016; IPCC, 2014c). In northern Africa, the number of heat wave days is expected to increase over the 21st century (Niang et al., 2014). For western Africa, the number of extreme rainfall days is forecast to increment. Eastern Africa, depending on the area, will see an enhancement of droughts and heavy rainfall. Regarding the southern Africa, more hot days and hot nights are expected together with a reduction of cold days and cold nights (Niang et al., 2014). Higher heat wave probabilities, combined with lower precipitation rates, are expected to be due to alterations in El Niño phenomenon, known as El-Niño Southern Oscillation (ENSO). Severe drought events are expected to affect the southwestern regions (Niang et al., 2014).

1.3 Africa and vulnerability

The African continent, especially the sub-Saharan Africa, is particularly vulnerable to climate change due to the overall low development, strong deficits in infrastructures, weak political settings and extreme poverty (Welborn, 2018). The World Bank (n.d.) designates it as the status of living on less than $1.90 per day, and the majority of people in extreme poverty (around 490 million people) live in the sub-Saharan Africa (Welborn, 2018). The future poverty increase represents a relevant constraint, especially facing climate change, as the number of people in extreme poverty is expected to reach the 590 million by 2040, and to slightly decrease by 2063 (Welborn, 2018). The vulnerability increases considering that on a demographic level, Africa has experienced the highest population growth in the past decades, and this trend will not slow down. Currently, the SSA is populated by roughly 1.6 billion, and will reach a population of 2 billion by 2050, and 4 billion 2100 (World Bank, n.d.; Serdeczny et al., 2016). Out of the total SSA population, 237 million people are undernourished (FAO and ECA, 2018). Africa's vulnerability also arises from another aspect. In fact, economically, it is highly dependent on climate-related activities (Serdeczny et al., 2016). The situation is dramatized by the fact that Africa has a low capacity to adapt to climate change (Welborn, 2018).

1.4 Agriculture in the SSA

Agriculture represents one of the most relevant sectors for a country's economy in the SSA. The region mainly relies on this economic sector with 65 % of the continent's labor force employed in it (Serdeczny et al., 2016). The SSA's agriculture is mainly rain-fed. As a matter of fact, 90% of the SSA staple food production comes from rain-fed systems (Cooper et al., 2008). Thus, this feature makes it extremely vulnerable to climate change considering the future precipitation trends and, overall, that this sector primarily relies on the environment and its biophysical characteristics (Pereira, 2017; Niang et al., 2014). In addition, the sub-Saharan's agriculture presents very limited technological inputs, financial capital and infrastructures, together with the fact that it is mainly for subsistence, dominated by smallholder farms (Pereira, 2017). Regional armed conflicts negatively affect the sector, representing a relevant constraint for its development (Kidane et al., 2006). The SSA has a significant amount of free land, which however cannot be used because of physical constraints, inadequate field management, political assets and lack of education (Kidane et al., 2006). These factors, together with drought stress, low and non-suitable field management, low soil fertility, pests, diseases and weeds are responsible for low yields in the region (Cairns et al., 2013). The SSA has experienced an economic stagnation until the mid 1990s. From that moment, a fairly significant production growth occurred, accounting for crops and livestock (also including fisheries and aquaculture) (OECD, 2016). Differently from other cases, e.g. Asia whose growth was driven by intensification, growth increases in the SSA occurred through area expansion and cropping systems' intensification (OECD, 2016). There are strong imbalances in terms of the regions and production, since the western Africa accounts for the majority of the total production (60%), while the southern Africa only for 22% (OECD, 2016). However, the crop sector dominates the agricultural production, accounting for 96% of the total (Serdeczny et al., 2016).

Maize is the most produced staple crop in the entire SSA, representing 30% of total area assigned to cereal production (Cairns et al., 2013). Depending on the area, other important staple crops are rice (eastern and western Africa), potatoes (eastern and central Africa), sweet potatoes (eastern Africa), cassava (western and eastern Africa) and plantains (eastern and central Africa) (OECD, 2016). Southern Africa is also known for a large fruits and vegetables production. All these products, maize in particular, sustain millions of lives in the SSA, guaranteeing the so-called food security (ten Berge et al., 2019). However, Van Ittersum et al. (2016) describe the SSA as the area with the most minor cereal self-sufficiency rate. Considering the future population growth that will characterize the SSA, many concerns are raising in relation to food security (Van Ittersum et al., 2016). Thus, a higher food demand is expected. By 2050, it is forecast to increment by 60% on a global level, in respect to the years 2005-2007 (Alexandratos and Bruinsma, 2012). By contrast, in the SSA it is expected to increase by 300% because of the fast population growth trend (Van Ittersum et al., 2016). Next to food demand, another issue is related to food availability. Therefore, the concern rises since climate change is expected to lower food availability and agricultural productivity, resulting in less affordable and available nutritious food, not enough to sustain all the lives (Serdeczny et al., 2016). The theory for which climate change will negatively affect maize production by lowering it is shared by many authors such as Blanc (2012), Cairns et al. (2012) and Lobell et al. (2011). However, Hachigonta et al. (2013) report the simulations on maize, millet and sorghum for the years 2010 and 2050 from a model called IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade). It projects a maize production increase for 2050.

1.5 Adaptation strategy: early and late maize varieties

As afore mentioned, different crops are cultivated in the SSA region, with maize being one of the most significant in terms of spread and production. Many studies, such as from Schlenker and Lobell (2010), Blanc (2012), Akpalu et al. (2008) have shown a decrease in maize yield through the use of global and regional climate models. Thus, in a World ruled by uncertainty and instability derived from climate change, it is essential to find some strategies able to tackle the issue. Therefore, when talking about climate change, three words always appear: mitigation, adaptation and resilience. The reason derives from the current knowledge on climate change, and the consequent necessity to take concrete actions towards its risks and impacts (Denton et al., 2014). Essentially, these practices are used to slow down this powerful change (mitigation), to adapt to an altered condition (adaptation) and to build up resistance to it (resilience). Since the sub-Saharan Africa is responsible for only 3.6% of the global CO_2 emissions (Cairns et al., 2013), in this frame it is more reasonable to focus on adaptation measurements rather than on mitigation strategies.

Many adaptation strategies are available. The literature suggests the most suitable maize variety in respect to a specific location and condition (Mabonga, 2017; Iken and Amusa, 2004; Cairns et al., 2013; Bello et al., 2012). The need derived from climate variabilities induced by climate change, e.g. in precipitation, which lead to an alteration of planting dates, preferring early or late planting (Mabonga, 2017). Therefore, a variety can be either early or late, depending on its genetics, sowing date, or both features (Iken and Amusa, 2004). An example of an early variety only related to its genetics is provided by Cairns et al. (2013), who mention recent genetic experiments on early maize varieties aimed at enhancing their drought and heat tolerance. While an example of the combination of both genetics and sowing date is given by Bello et al. (2012), who base their study on early planting drought tolerant maize varieties. However, early maize varieties can also only be related to their early sowing date. In this regard, considering that maize is particularly sensitive to droughts in its flowering phase, early planting is preferred since it would avoid a possible drought condition that comes along with the climate condition (Morris, 2001). The environment in which the crop grows is indeed very significant, and can also affect the crop's yield potential (Asghar et al., 2010). Furthermore, Mati (2000) supports the theory for which the planting date significantly influences maize yields.

Nevertheless, depending on the area, different planting dates can be employed. For instance, a study carried out in Nigeria by Bello et al. (2012) suggested early sowing maize varieties as a possible adaptation strategy in opposition to late maize varieties. The early sowing date (around the beginning of March) corresponds to the onset of the rainy season, before it is at its peak and, consequently, the harvesting date comes earlier. The advantage of planting earlier is that food stocks are still available for the month of July. In fact, usually by then, they are already depleted by the dry season that characterizes the area. In contrast, the late type is planted in between July and August, during the second rain cycle, which usually ends with a final drought, differently from the first cycle. A study based in Nigeria by Iken and Amusa (2004) showed that the optimum planting time corresponds to the start of the rainy season. In addition, a study set in Ghana by MacCarthy et al. (2018) shows lower maize yields due to late planting (third week of July). Dahmardeh (2012), through an experiment in Iran, proved that a planting date on August 5th had more significant results in term of yields than a planting in July. However, from these different studies it is evident that the most suitable maize type needs to be selected in relation to the geographical location, considering climate conditions and other specific factors such as soil type, moisture and fertility (Cairns et al., 2013; Ramirez-Cabral et al., 2017; Mati, 2000). In order for a maize crop to properly grow, it is essential to consider the right establishment for the crop in terms of time and location, nutrition, disease and pest control, an adequate field management, harvesting method and storage (Iken and Amusa, 2004).

1.6 Why are models used?

In a frame of threat and necessity to face the possible impacts of climate change, climate modelling plays an essential role for the prediction of future climate trends. The Intergovernmental Panel on Climate Change (IPCC) elaborated four representative concentration pathways (RCPs), each distinguished by their total radiative forcing pathway (IPCC, 2014c). In ascending order, the RCP2.6, 4.5, 6 and 8.5 range from the mildest to the strongest (IPCC, 2014c). RCPs have been largely employed in the research world since, once fed into climate models, they simulate the climate responses to altered forcings in terms of temperature, rainfall and all the variables available from the model. Significant uncertainties can often characterize models. For instance, according to Rowell

(2012), there are higher uncertainties in precipitation projections rather than temperature projections. This is related to a constraint in precipitation modelling due to its elevated spatial and seasonal dependence, which is higher than temperature projections (Orlowsky and Seneviratne, 2012). Many more can be listed in relation to different input parameters, depending on the model. However, once the output is generated, a clearer, hypothetical global or regional scenario can be drawn. Therefore, it is an useful tool for manifold actors ranging from researchers to policy-makers (Adnan et al., 2017). In parallel, crop models exist and, once fed with climatic data, allow the simulation of agricultural productivity as a function of variabilities induced by climate change (Adnan et al., 2017). Considering the level of vulnerability of the agricultural sector, crop models play a very significant role for future. Recently, the crop model AquaCrop developed by FAO has been employed in the research world. It is able to simulate crop yields under climate change scenarios (Steduto et al., 2012; Farahani et al., 2009; Ngetich et al., 2012). Therefore, the model results particularly useful in decision-making processes and strategies such as climate impact assessments and adaptation strategies (Greaves and Wang, 2016).

1.7 Study aim and hypothesis

Climate change will have major global implications, and very adverse for the highly vulnerable agriculture in the sub-Saharan Africa. Therefore, studying the possible climate impacts, and relative strategies able to ameliorate the condition, is fundamental. The aim of this study is to analyze how climate change will affect maize yields in the sub-Saharan Africa in a case study of Kenya. Because of the area's vastness and relative high climate variability, three locations in the state of Kenya were selected for the models simulations. Each site has different climate conditions, soil profiles and biomes. Therefore, it is possible to capture a high variability of conditions and, consequently, how climate change will affect agriculture in different areas. The study will be executed using two distinct pathways. On one side, simulations will be run with the crop model AquaCrop for early and late maize in the three locations both under irrigation and field management conditions, and without, over the time range 1951-1955, 2015-2019 and 2091-2095 under the RCP8.5. The crop model allows the simulation of maize yields and biomass (Steduto et al., 2012). In parallel, important temperature-dependent maize development thresholds will be specifically analyzed.

The research is based on two hypotheses: 1) climate change will lead to lower maize yields. 2) early sowing maize varieties result more suitable than late sowing maize varieties in adaptation strategies since they allow a higher yield production. Furthermore, the suitability of AquaCrop in analyzing maize production under climate change scenarios with only year-by-year simulations will be discussed.

2. Background

2.1 Cereals in nutrition

From the *Gramineae* family, cereals, basically edible seeds, have characterized the human diets for many centuries (McKevith, 2004). Globally, different types of cereals exist, but maize, rice and wheat account for the highest consumption (94% of the total cereal consumption) (Ranum et al., 2014). The consumption patterns change by country, with rice being preferred in Asia, and wheat in central Asia, the Middle East, North and South America, and Europe. Maize is mostly used in southern and eastern Africa, Central America, and Mexico (Ranum et al., 2014). Cereals represent a relevant source of nutrition for humans, in terms of both macro (fount of carbohydrates, proteins and fibers) and micronutrients (e.g., vitamin E, zinc, magnesium) (McKevith, 2004). Their nutritional content also depends on how the cereal is treated after the harvest. In fact, the macro and micronutrients are mainly concentrated in the outer part, thus if removed during the milling, they have less nutrients (McKevith, 2004).

2.2 Cereals and food security

In recent years, the word "food security" has appeared. Its definition has been modified multiple times throughout the second half of the 1900, to finally reach its complete and globally shared declaration in 1996. The World Food Summit (FAO, 1996) defined it as when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life. In the SSA region, food production, import and food aids mostly guarantee this condition (Kidane et al., 2006). Maize, rice, wheat and other minor coarse grains are produced in the SSA, with maize being the most significant in terms of quantity. These cereals partly guaranteeing the so-called food security (OECD, 2016). The word "partly" is used since, according to Kidane et al. (2006), considering the future population growth, the overall poverty and low economic development, cereal production is still not enough to fully support the current and future SSA population. In order to meet the food demand, many countries started to import around 25% of cereals (Kidane et al., 2006). Nevertheless, some parts of the region are found in a chronic undernourishment condition (Kidane et al., 2006). The situation can be worsened by drastic changes affecting the climate and climate extreme events and, consequently, agricultural outputs (Kidane et al., 2006).

2.3 Maize in general

Maize (Latin name, *Zea mays*), also known as corn, is a staple crop that originated around 7,000 and 10,000 years ago in Mexico, as archeological evidence supports (Ranum et al., 2014). Some other theories and evidences show other geographical origins such as the Himalayan region, and in the high Andes of Ecuador, Bolivia and Peru (Ranum et al., 2014). Different indigenous tribes brought maize from its original location to other parts of Latin America and the Caribbean, and successively to the United States and Canada. It reached Europe only when the European pioneers époque started, and later on it was taken to Asia and Africa (Ranum et al., 2014). However, from its initial domestication, in more recent years maize started being object of genetic modifications and new, complicated methodologies (Ranum et al., 2014). In recent times, according to FAOSTAT (2017), the United States are the largest maize producers, followed by China and Brazil.

From a nutritional perspective, maize has a lower protein content than rice and wheat, but it furnishes higher energy levels in terms of Kcal/g. Maize is also rich in micronutrients such a different B vitamins and minerals. However, it is low in calcium, folate, and iron, and lacks in vitamin B12 and vitamin C (Ranum et al., 2014).

There are different types of maize, depending on the kernel, which is the actual maize seed. One of its most important and distinguishable features is the color, and it ranges from yellow to white, red and black (Ranum et al., 2014). In the United States, for instance, yellow maize is the most used, while the white kind is more spread in the African continent. In addition, the variety is also shaped by the endosperm, determined by its size and composition. It can result in different types such as dent, flint, waxy, flour, sweet, pop, indian, and pod corn (Ranum et al., 2014). As science progressed, genetically modified (GM) herbicide-resistant maize types have been introduced. This innovation raised two different attitudes among the public opinion: opponents and supporters. Even though the topic will not be further developed, it had to be mentioned in relation to maize production, especially since in some countries GM maize crops became the most commercialized in the market. In the United States, for instance, 85% of the total maize crops are genetically modified (Ranum et al., 2014).

2.4 Maize growth

Maize is a C_4 plant. Differently from C_3 plants, these types developed an alternative photosynthetic process in response to the arid and warm environmental conditions that they grow in, resulting very tolerant to it (Crafts-Brandner and Salvucci, 2002). Thus, it still allows them to efficiently establish a high photosynthetic rate when temperatures are elevated, and to avoid the process of photorespiration. During the Calvin cycle, they produce a four-carbon sugar which can take more CO_2 to the RuBisCO enzyme (Crafts-Brandner and Salvucci, 2002).

According to FAO (n.d.), maize growth develops on four stages: initial, crop development, mid-season and late season. In terms of phases, the initial stage comprehends the emergence, which corresponds to the very first beginning of the cycle, and it is part of the establishment phase, of usually a length of 15 to 25 days. The vegetative stage of the crop development occurs at 25-40 days, followed by the mid-season stage. During this phase, flowering occurs, with a duration of 15 to 20 days. The late season stage comprehends the yield formation (35-45 days), and ripening (10-15 days) (FAO, n.d.).

Among the different cereals, maize has the highest yield growing potential which is very susceptible to the environment in which it grows (FAO, n.d.; Asghar et al., 2010). However, its growing conditions depend on certain climatic conditions. Maize is cultivated in climates that range from temperate to tropic. It requires a daily mean temperature of above 15 °C, and frost-free (Du Plessis, 2003). The length of the growing season depends on temperature (FAO, n.d.). According to the different temperature ranges, when the mean daily temperatures are above 20°C, early maize varieties require 80 to 110 days to mature, while medium varieties take a longer time, 110 to 140 days. On the other hand, during the growing season, when temperatures are below 20°C, the cycle takes a longer length (FAO, n.d.). Maize is very sensitive to frost, thus low temperatures do not pose optimal growing conditions. Consequently, when the daily mean temperature is between 10 and 15°C, maize is mostly cultivated for forage purposes. In fact, cooler conditions affect negatively the seed set and the grain maturity (Du Plessis, 2003). Maize only germinates above 10°C, while the most optimal temperature is between 18 and 20°C. On the other hand, if the crop is sensitive to frost, it is instead extremely tolerant to hot and dry atmospheric condition. The only requirement is that the plant receives sufficient water, and that temperatures do not exceed 45°C (FAO, n.d.).

Radiation is another important factor for maize growth (FAO, n.d.). However, for the crop to develop, it is necessary that light penetrates only five or six leaves above the cob. Water largely affects the crop growth. A medium maturity grain crop usually requires between 500 and 800 mm of water, depending on the climate (FAO, n.d.). Sowing methods and spacing (usually between the rows there is 0.6 and 1 meter) can vary. In respect to the soil profile, maize grows on any type. However, it is preferable to not be very dense clay and very sandy, otherwise it turns into a constraint for the crop growth. The texture classes of loamy sand, sandy loam and sandy clay loam, defined in the official soil textural classification, are the most suitable for maize growth because of their adequate air and moisture levels (Du Plessis, 2003; USDA, 1987). Therefore, since maize is sensitive to waterlogging, the soil should be well- aerated and drained (FAO, n.d.). Maize requires high levels of fertility. Thus, adequate nitrogen levels are fundamental for the crop growth (Shiferaw et al., 2011). Maize grains take up to around 200 kg/ha N for the highest producing varieties. Fertilizer can boost maize yield by 40/45% (Asghar et al., 2010). Overall, the most general and basic requirement for maize growth is that soil fertility is maintained (FAO, n.d.). In respect to salinity, maize crops are fairly sensitive to it, as yields decrease when soil salinity increases.

2.5 Maize consumption

As the latest data available shows, 1,134,746,667 tonnes of maize have been produced in 2017, accounting for the entire globe (FAOSTAT, 2017). Thus, worldwide, maize is produced in relevant quantities, and the demand is high (Ranum et al., 2014). This derives from the diversification of its use (Greaves and Wang, 2016). In fact, it can be used for food purposes, as it can be processed into different products such as flour, tortillas, corn starch, tortillas, and many more (Rouf Shah et al., 2016). Another relevant part of maize production is designated to livestock and poultry feed. The majority of the human diets are meat based, thus leading to a high demand of livestock. As they necessitate adequate nutrition, more maize grains are required, whose prices rise as demand increases (Shiferaw et al., 2011). The consequent price increase results in less product availability for poor consumers, as they cannot afford it (Shiferaw et al., 2011). Contemporaneously, the global market has seen the coupled high demand, and consequent, price rise in the biofuel sector (Klopfenstein et al., 2013). Since the past decades, maize production has also been employed in the production of biofuels, especially in the United States (Klopfenstein et al., 2013). In fact, ethanol can be obtained from maize through some chemical processes (Ranum et al., 2014). In contrast, the biofuel industry in the SSA accounts for less than 1% of the total global market (OECD, 2016).

Maize has been exported worldwide from its original area, finally reaching the African continent in relatively recent times (Shiferaw et al., 2011). Nowadays, it represents one of the most important staple crops for the continent, together with the traditional millet and sorghum crops (Shiferaw et al., 2011). Thus, its introduction lead to a change in the consumption pattern and eating habits (Shiferaw et al., 2011). However, the sub-Saharan Africa presents two specific features in relation to maize production. Firstly, differently from many other countries, maize is produced on a smallholder scale and mainly for subsistence. Thus, maize acquires the value of a staple crop rather than of a cash crop. These two terms refer to a crop that, as in the first case, is produced with the prime purpose of sustaining its own producers. Therefore, they provide to the household's food security (Oseni and Winters, 2009). On the other hand, a cash crop is produced with the intention to be sold on the market (Oseni and Winters, 2009). Another distinctive feature of the sub-Saharan Africa (except for some areas in west Africa) is the preference for white maize instead of the yellow type, which represents 96% of the world maize trade (Shiferaw et al., 2011). According to Ranum et al. (2014), this preference also derives from the perception of the social status, since yellow maize is connected, among the popular opinion, to food-aid programs, and is associated with poverty. Besides this, it is simply a matter of tradition: in the African continent, local populations are used to eating white maize rather than yellow (Ranum et al., 2014). In terms of numbers, 25 million hectares are occupied by maize cultivations in the sub-Saharan Africa (Shiferaw et al., 2011). As mentioned before, it is primarily under a smallholder system. Differently from high income countries where a relevant part of maize production is assigned to livestock feed (70%), in the sub-Saharan Africa only 18-20% is designated to animal food, and more than two thirds to human nutrition (Shiferaw et al., 2011).

2.6 Climate sensitivity

Maize crops are very susceptible to rainfall and temperature variability (MacCarthy et al., 2018; FAO). Many studies have focused on those parameters, both considered singularly and combined. Regarding temperature, some authors find it as the main variable affecting maize yields. Liu et al. (2008) found the optimal maize growth temperature at 25°C. When this threshold is crossed, Lobell et al. (2011) found that under optimal rain-fed conditions a 1% yield reduction occurs per each degree over 30°C. Under drought conditions, there is a 1.7% decrease. On the other hand, some authors have found the highest dependency of maize yields on precipitation. A survey-study carried out by Rivington and Koo (2011) analyzed different crop models and the crops' answer to climate variability, discovering that precipitation variations influence crop yields the most. In this regard, Waha et al. (2013) observed that a 30% in maize yield reduction is triggered by a reduction in wet season precipitations. Differently, a shorter wet season, under the condition that mean precipitations are not modified, does not affect maize yields (Waha et al., 2013).

The influence of these two climate variables can also be analyzed jointly since maize production in SSA is influenced by an interdependence between precipitation and temperature (Blanc, 2012). In their research, Cairns et al. (2012) proved that the coupled increased temperature and decreased rainfall negatively affects maize growth and production. Maize also needs be mentioned in relation to CO_2. As a C_4 plant, one of its features is to be significantly indifferent to CO_2 increases (Yavaş and Ünay, 2015). However, Chijioke et al. (2011) found higher CO_2 concentrations beneficial for maize growth and development by a higher photosynthesis stimulation. Considering the future projected CO_2 increases (Niang et al., 2014), Yavaş and Ünay (2015) did not detect reduced maize growth in a condition of coupled CO_2 and temperature increases under adequate irrigation conditions, but negative effects were visible with reduced irrigation.

Maize can be subjected to different stresses. Among them, the crop is extremely sensitive to heat stress during the reproductive phase, and to droughts during its flowering phase (Dupuis and Dumas, 1990; Cairns et al., 2013). On the other hand, cold conditions represent a relevant stress for maize as a C_4 plant (Steduto et al., 2012). In addition, Çakir (2004) found moisture stress as a significant constraint for maize development. Even though the crop can tolerate water deficiency during the vegetative and ripening stages, it can be very adverse in the tasseling phase (part of the flowering stage). For this reason, according to FAO (n.d.), in conditions of water shortage due to low rainfall and limited irrigation supply, the flowering and yield formation stages should be the prioritized ones. Overall, water stress represents an extremely relevant concern, with water shortage negatively affecting maize growth and yield production by lowering it (Steduto et al., 2012). Water stress arises from the absence of water and irrigation, especially when there is no water in the root zone, and plant processes get directly affected (Steduto et al., 2012). The root zone should always be watered, especially after sowing. For this reason, adequate irrigation practices are fundamental. Factors such as irrigation depth and frequency can optimize maize yields (Du Plessis, 2003). Therefore, considering the levels of maize sensitivity to the climate and high exposure to stress, their detection is crucial to increase its resilience (Leng and Huang, 2017).

2.7 Crop models

Undoubtedly, crop models play a relevant role by allowing the simulation of crop production in response to climate change conditions (Bassu et al., 2014). Process-based crop models suit better than empirical models in a climate change study context since they take into consideration the responses of physiological processes of crop development. Simultaneously, they account environmental and management parameters (of a variable nature), and the response of crops to climate variations (Bassu et al., 2014). Crop models also allow the planification and development of adaptation strategies to climate change and impact assessment (Bassu et al., 2014). Many crop models exist and are created with diverse purposes and objectives. Some models might be better than others at simulating future responses, as some might be more efficient in representing past rather than future conditions (Bassu et al., 2014). For this reason, it is important that the uncertainties related to each model are reported, together with the use and purpose of the model. Thus, it is possible to decide what model suits a research, and the actual studied condition, better (Bassu et al., 2014). Some authors such as Bassu et al. (2014) and Tao et al. (2009) report the necessity to consider different outputs of multiple models since one model is not enough to capture all the actual and relevant processes.

In relation to maize, many models are able to simulate it in relation to different climate scenarios and time spans. Bassu et al. (2014) furnish an elaborated analysis on how different maize models respond to climate change factors. MacCarthy et al. (2018) suggest a holistic approach accounting the soil-water-management interactions for maize crops. General Circulation Models (GCMs) are useful when simulating changes in the climate on a global scale, and have been largely employed in this field. Tesfaye et al. (2015), for instance, have modelled maize in the SSA under climate change scenarios in order to see its possible outcomes using the model CERES–maize, feeding it with climatic data from two GCMs (MIROC and CSIRO). However, lately, Regional Climate Models (RCMs) have been largely employed. They are driven by GCMs, which create the boundary conditions for the area that the RCM will model. Differently from GCMs, regional climate models provide more detailed information at a higher spatial resolution, and on a smaller scale, considering the local forcings (Lennard et al., 2018). This main advantage gets translated into the possibility to see the change in interannual variabilities that characterize the area at a local scale (Arnell, 2003). This feature explains why they are primarily employed in the formulation of mitigation and adaptation strategies.

FAO developed a crop model called AquaCrop which is able to simulate attainable and actual crop yields in response to environmental stresses and climate change scenarios (Steduto et al., 2012; Farahani et al., 2009; Ngetich et al., 2012). This model is particularly suitable in conditions of water scarcity, disadvantaging factor for crop production. Therefore, it suits studies focused on the SSA region, as it is one of the main water scarcity areas on the Planet (Ngetich et al., 2012). The literature highlights its accuracy, simplicity and robustness, together with its relatively small number of input parameters (Farahani et al., 2009; Greaves and Wang, 2016; Wamari et al., 2007).

2.8 Adaptation strategies

Adaptation strategies are manifold and of different natures. For instance, many authors such as Cairns et al. (2013), Holden and Fisher (2015), Bello et al. (2012) suggest the need for drought-tolerant crop varieties facing the progressive, and forecast, water limitations. Different authors also propose the adoption of early or late sowing maize varieties (Holden and Fisher, 2015; MacCarthy et al., 2018; Dahmardeh, 2012). An adaptation practice can also concern farming practices. Therefore, the introduction of efficient farming practices is also suggested, even though low education levels of smallholder farmers might result in a constraint for their application (Holden and Fisher, 2015). However, practices aiming at reducing water run-off and evapotranspiration, e.g. residue retention and mulching, together with adequate artificial irrigation practices are proposed. In addition, since maize requires determined levels of soil fertility, they can be increased by the adoption of fertilizers and manure (MacCarthy et al., 2018). Weed management is also mentioned as a relevant part of management practices (MacCarthy et al., 2018). In this frame, irrigation practices are also suggested. However, the type of agriculture practiced in the sub-Saharan Africa is still quite traditional in comparison to the modern agricultural practices. When considering irrigation practices, flood irrigation methods are employed, since it does not require much economic investment and specific knowledge (Kori et al., 2017). However, this type of method leads to a higher water wastage. Therefore, the usage of more modern methods such as the sprinkler and drip methods can improve irrigation efficiency, even though they present higher costs and maintenance, that smallholder farmers cannot afford (Kori et al., 2017). Considering the smallholder system that characterizes the SSA, in a study based in Kenya, Bryan et al. (2013) suggest another practice that fits the setting: agroforestry. Even though it has been existing for many centuries, only recently it has gained more attention. FAO (2015) defines it as a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels. However, as Bryan et al. (2013) remark, in order for it to work, a minimum level of knowledge and investments are necessary, together with a solid social network.

3. Material and methods

3.1 Aquacrop

In this study, the crop model AquaCrop version 6.1 developed by FAO is employed. It is retrievable from http://www.fao.org/aquacrop. AquaCrop is a dynamic model, and it simulates attainable and actual crop yields as a function of water consumption and of environmental conditions, including climate change scenarios (Steduto et al., 2012). However, it does not consider the effects of diseases and pests. Its main functioning is based on the following equation:

$$B = WP \cdot \Sigma Tr \qquad (1)$$

where B is the biomass produced cumulatively in kg per m^2, WP is the water productivity parameter (either in kg of biomass per m^2 and per mm, or in kg of biomass per m^3 of water transpired), and Tr represents the crop transpiration either mm or m^3 per unit surface.

The second equation on which AquaCrop is based is represented by:

$$Y = HI \cdot B \qquad (2)$$

where Y is the yield, B is biomass and HI is the harvest index, which is the ratio of yield to biomass. The harvest index modifies the part of biomass that will be harvestable (Steduto et al., 2012). AquaCrop only accounts for the partitioning of biomass into yield, and not for the partitioning among the different plant organs. This is due to the high complexity of the partitioning processes, therefore it avoids possible uncertainties that arise from them (Steduto et al., 2012).

Hence, AquaCrop's functions are based on equation (1) and (2), and it is characterized by a set of model components: climate, crop, soil and management. The model runs on different climate parameters which can be chosen from maximum and minimum air temperature, evapotranspiration (ETo) and rain. In addition, each run is fed with CO_2 concentrations which can be selected according to different scenarios or external data. AquaCrop can simulate various crops (e.g., potato, maize, tomato and many more) which have already been calibrated by the FAO developers. The model includes the crop's subcomponents such as phenology, canopy cover, rooting depth, crop transpiration, soil evaporation, biomass production and harvestable yield. When considering the specific crop parameters, a full or limited set can be selected. Overall, the model can consider the crop's development, response to stress such as water stress (e.g., sensitivity or tolerance of canopy development to water stress), temperature (pollination, crop development and transpiration affected by heat or cold stress), salinity (tolerance or sensitivity to low or excessive salinity levels and the crop's response to it in canopy cover and stomatal closure), and soil fertility (the crop can be sensitive to it and, if considered, a local calibration can be done). In AquaCrop, it is possible to select the canopy development and growth in calendar days or growing degree-day (GDD). The GDD principle considers the crop's growth in relation to a temperature threshold for which, when above it, the plant starts growing. Therefore, that "exceeding" number is calculated for the GDD value (Ojeda-Bustamante et al., 2004). In more simple words, it is the sum of temperature above the specified limit. In this study, the limit was set at 8°C (GDD8)(Table 1). Therefore, Furthermore, the model can consider the crop's growth stages (according to FAO) in relation to calendar days. AquaCrop considers management practices such as irrigation and field management. In respect to irrigation, it can simulate both under rain-fed and irrigation conditions. Under management conditions, sprinkler, surface or drip can be selected, each characterized by a specific time schedule, depth and quality of the water. Otherwise, AquaCrop can simply simulate with an automatic schedule. In respect to field management, it is relatively limited to only a few aspects. AquaCrop considers the soil's fertility for the crop growth (it can be naturally fertile or induced by fertilization), the mulching of the soil aimed at reducing soil evaporation, and the use of small dykes to pond water or the control of surface runoff. The model does not directly simulates fertility effects on crop growth (Steduto et al., 2012). Weed management is also part of field management options, and its degree can vary (e.g. it can be optimal, moderate or non-present). In addition, different soil profiles and groundwater values can be selected. AquaCrop can vertically subdivide the soil up to 5 layers of variable depths. Despite the number of layers, also called horizon, AquaCrop always accounts for 12 soil compartments.

In parallel, another set of simulations was run using the program Matlab, currently widely employed in climate impact assessments. It can be used for multiple purposes as it can create models, develop algorithms and analyze data. In this study, a Matlab script was created and run with the ultimate purpose to provide detailed information regarding the exceedance of temperature thresholds for maize growth, as defined in AquaCrop, over the time range 1951-2100 (divided into 30 years-time spans). Three grid cells, corresponding to the three sites, with specific climate data, as in AquaCrop, such as temperature, precipitation (in mm), evapotranspiration (in mm/day) and CO_2 concentration (RCP8.5) were used as input to the script. In respect to temperature, there were maximum air temperature in °C (Tmax), minimum air temperature in °C (Tmin), and their mean (Tmean). Different maize growth parameters are set, and are listed in Table 1.

Table 1. List of maize growth parameters set.

Maize growth parameters	**Equation**	**Unit**
sowing date		Calendar day
base temperature below which the crop does not progress	Tmean<8	°C
base temperature above which the crop does not progress	Tmean>30	°C
minimum temperature below which pollination starts to fail (cold stress)	Tmin<10	°C
maximum temperature above which pollination starts to fail (heat stress)	Tmax>40	°C
Growing cycle, set in: - total length - from sowing to emergence - sowing to flowering - from sowing to maturity	GDD8=80 GDD8=880 GDD8=1700	GDD

The employment of both modelling tools resulted in complementary information. As a matter of fact, AquaCrop generated outputs in terms of maize yields and biomass. The Matlab script was run to analyze the occurrence of weather events exceeding important temperature dependent thresholds on maize development (Table 1). Therefore, the final biomass and yields can be related to the exceedance of developmental thresholds and general trends in temperature, precipitation and evapotranspiration. In addition, it is a matter of temporal scale simulation. AquaCrop only simulates for 15 years, each divided in three time slots thus resulting into the following: 1951-1955, 2015-2019, 2091-2095. Differently, the simulations run in Matlab are on a longer, and continuous, time scale which covers from 1951 to 2100. In order to better capture the on-going trends, time periods were of 30 years each (section 3.2). Therefore, this feature gives a more complete and less fragmented knowledge of the on-going dynamics.

3.2 Climate data

Both AquaCrop and Matlab were fed by the climate data retrieved from the Coordinated Regional climate Downscaling Experiment (CORDEX) which involves several meteorological institutes and equally diverse RCMs (regional climate models) (CORDEX, n.d). This regional climate downscaling technique is a new experiment promoted by the World Climate Research Program (WCRP). It presents 14 different regions (domains), and the African domain was selected for this study. For every domain, the area is covered of grid cells with a spatial resolution of approximately 50x50 km. As a regional climate model (it can also be called regional climate downscaling), its driving data comes from different RCMs which, in turn, retrieve it from different GMCs, and generates simulations for each selected RCP scenario (Giorgi et al., 2009). Essentially, GCMs can simulate climate change scenarios on very large scales (Arnell, et al., 2003). Thus, they are suitable for climate projections on a global scale. However, this feature implies that they are not able to fully capture regional and local climate variabilities (Paeth et al., 2011). Therefore, RCMs are crucial for local and regional impact assessments and planning since they are able to simulate on smaller scales (Arnell et al., 2003). Therefore, this choice suits better this research. An advantage of RCMs is their ability to capture the principal climatological rainfall features. However, their accuracy depends on the specific model, season and region (Nikulin et al., 2012; Paeth et al., 2011).

In this study, the climate data was retrieved from the domain AFR44 whose data was obtained by the RCM RCA4 by SMHI which, in turn, was driven by the GCM CanESM2 (developed by the Canadian Center for Climate, CCC). Data for temperature, ETo and precipitation was used for the time period 1951-2100. In this study, the simulations were divided into 30 year climate periods: 1951-1980, 1981-2010, 2011-2040, 2041-2070, 2071-2100. CO_2 concentrations were distributed from AquaCrop, and represented the RCP8.5 scenario for the future time period. Three grid cells in Kenya were used, corresponding to three sites characterized by different climates, biomes and soil profiles (Table 1, Fig. 1). One site is located on the coast at latitude 3°54'24.19"S and longitude 39°44'59.44"E. The site situated in the Central area is at latitude 1°24'9.16"S and longitude 37° 3'25.45"E, and at 1635m of altitude. Last, a site localized in the shrubland of the northern part is at latitude 3°0'23.86"N and longitude 39° 1'31.32"E.

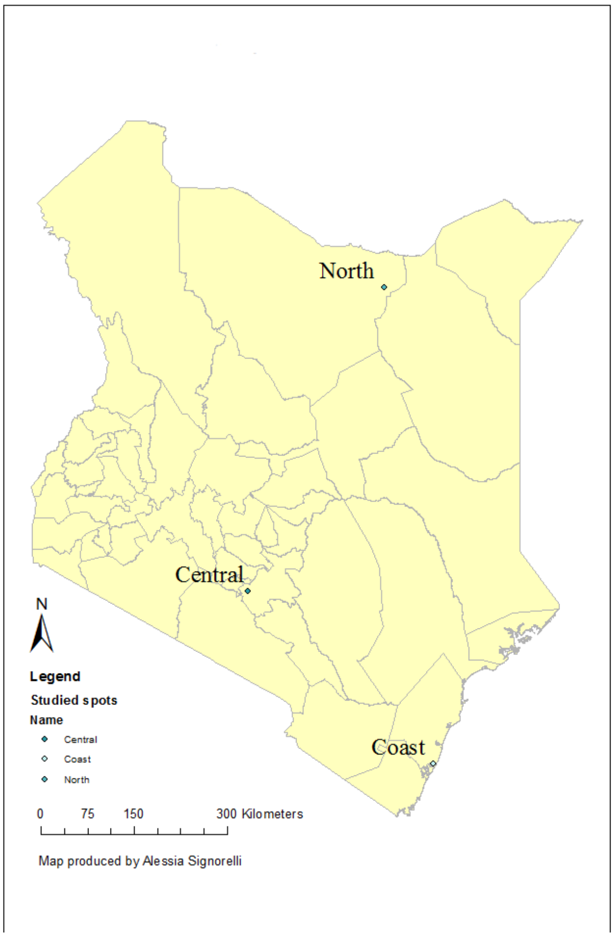

Figure 1. Map of Kenya showing the location of the three studied sites.

3.3 Data treatment and analysis

With AquaCrop, Maize GDD yields and biomass were simulated for both early and late sowing maize in three sites in Kenya, with and without irrigation and field management practices.

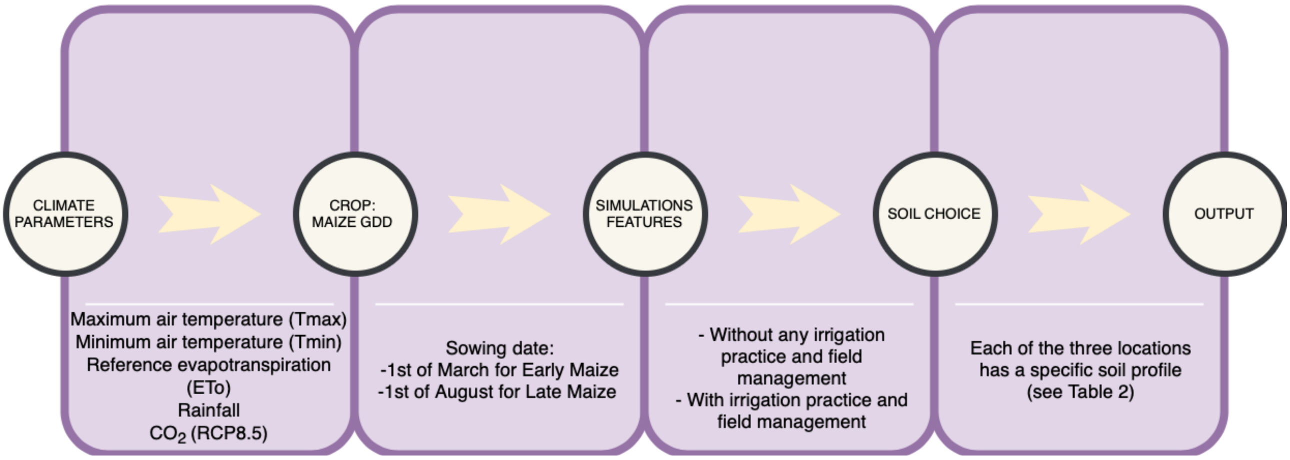

Figure 2. Diagram showing the conceptual steps for running AquaCrop for each of the three sites and time periods (1951-1955, 2015-2019, 2091-2095).

The climate parameters were Tmax, Tmin, ETo, rainfall, CO_2 concentrations according to observed trends and to the RCP 8.5 scenario. The already calibrated Maize GDD crop was selected, inserting March 1^{st} as sowing date for early maize, and August 1^{st} for late maize. During its development, the crop was not under water, temperature, salinity or soil fertility stress. Due to the model limitation of simulating only year by year, the simulations were run for each of the years ranging from 1951-1955, 2015-2019 and 2091-2095. Two kind of simulations were run. The first one without any kind of irrigation practices and field management. While the second one had optimal irrigation and field management conditions. A sprinkler wetting 100% of the surface was employed as irrigation method. While as field management practices, soil fertility was selected as a not limiting factor for biomass production, the soil was 100% covered by mulches (derived from organic plant materials), field surface practices were preventing runoff, and weed management was perfect. The soil profile could be chosen. ArcMap was employed to detect the exact soil type for each of the three sites. Firstly, the sites were localized with Google Earth, and the coordinates/points were saved as a kmz file. Successively, in ArcMap, a shapefile of the country of Kenya was inserted, together with the shapefile of the soil type according to the FAO (1974) soil classification. The second step represented the conversion of the kmz file to layer in order to detect precisely which kind of soil characterized each of the three locations and listed in Table 2.

Table 2. Data of the coordinates, soil profile and biome of the three locations in Kenya.

	Coordinates	Soil profile	Biome
Coast location	Latitude: 3°54'24.19"S Longitude: 39°44'59.44 "E	Luvisol ferric (AquaCrop as clay)	Tropical, subtropical moist broadleaf forest
Central area	Latitude: 1°24'9.16"S Longitude: 37° 3'25.45"E	Vertisol eutric (AquaCrop as sandy clay loam)	Tropical, subtropical grassland, savanna, shrubland
Northern part	Latitude: 3°0'23.86"N Longitude: 39° 1'31.32"E	Leptosol lithic (AquaCrop as sand, low depth)	Desert and xeric shrubland

Each simulation generated various outputs, but only crop development and production were analyzed. In specific, the analysis concerned the modelled biomass (to/ha) and yield (to/ha). Boxplots were then produced.

A statistical analysis was performed for both the simulated yield and biomass, and the climatic forcing's, through a two-way ANOVA test. Essentially, this technique allows to check if the results are significant (McDonald, 2014). It is based on one dependent variable, and two or more independent variables. In this case, when the two-way ANOVA test was performed for the AquaCrop output on biomass, biomass was the dependent variable. The independent variables were represented by the site (Central, North, Coast), the time period slot (1951-1955, 2015-2019, 2091-2095) and the type (early or late sowing maize). The same procedure was executed for the AquaCrop yield output. In this case, yield was the dependent variable, while the just afore mentioned were kept as independent variables. Another test was performed for harvest DOY (dependent variable), and site, time period slot and type as independent variables. Furthermore, another two-way ANOVA test was performed for biomass and yield in relation to the presence or absence of treatments (irrigation practice and field management). In this case, biomass, in one test, and yield, in a second test, were dependent variables, while treatment and type (early and late maize) were the independent variables. Furthermore, the two-way ANOVA test was executed for the average temperature during the early and late maize growth (Tmeangrowns). As dependent variable, it was tested to check the significance with the type (early and late maize), time period (1→ 1951-1980, 2→ 2011-2040, 3→ 2071-2099) and site (Central, North, Coast).

4. Results

4.1 Aquacrop results

4.1.1 Biomass

The results from the AquaCrop model simulations of early maize biomass vary substantially among the three sites characterized by different bioclimatic conditions under climate change effects (Fig. 3A). The simulations were performed under management effects (irrigation and field management). The early maize biomass for Central decreases by almost 5to/ha during the future scenario, in respect to the past simulated trends. For North, they are relatively low and do not show a significant change during the different time periods. For Coast, the biomass values are significantly high (around 13 to/ha) for the time periods 1 and 2, and are projected to decrease considerably to less than 10 to/ha during 2091-2095. Decreases in early maize biomass, without management effects, are projected in the future scenario for each site (Fig. 3B). In Central, from an initial average value of around 5 to/ha, an increase is visible for the middle period (2015-2019), while a decrease is projected during the third time period. Similarly to the results for North in Fig. 3A, the overall biomass in North, without any kind of treatment, results quite low (< 5 to/ha) for the three time periods. In respect to Coast, the average biomass decreases from the initial high value (around 12 to/ha) of 3.1 to 3.3, when the value is projected to drop under 10 to/ha. Slight early maize biomass increases are notable for the simulations with treatment (Fig. 3A) in respect to the early maize simulations without (Fig. 3B). The most evident are for sites 1.1 and 1.2 (Fig. 3A), which have higher values in respect to the sites 1.1 and 1.2 (Fig. 3B). Site 2.1 (Fig. 3A) has higher values than site 2.1 (Fig. 3B). However, overall, for the remaining sites, there is not a remarkable difference in biomass values under or without treatment.

The results from the AquaCrop model simulations of late maize biomass vary substantially among the three sites characterized by different bioclimatic conditions, under climate change effects (Fig. 3C). The simulations were performed under management effects (irrigation and field management). For Central, biomass decreases substantially from the time period 1 to time period 2. It is projected to slightly increase during time period 3, but not reaching the simulated values from time period 1. In North, a progressive biomass increase occurs and is projected over the three time periods. The maximum value is projected to reach 5 to/ha. In respect to Coast, an elevated biomass of around 17 to/ha is simulated for time period 1. The value drops under 15 to/ha for time period 2, and is projected to increase of just a few to/ha in time period 3. Decreases in late maize biomass, without management effects, are projected in the future scenario for each site (Fig. 3D). For Central, from a 10 to/ha biomass, a decrease occurs during the time period 2015-2019, and is projected to rise for the last time period with a similar value as the initial one. For North, a progressive increase occurs in time period 1 and 2, and is projected for time period 3. Coast shows an initial final biomass average of around 16 to/ha for the first time period. A significant drop characterizes the second time period, while a slight increase is projected in time period 3. Overall, there is not a significant difference in the biomass for the simulations under and without treatment. However, more in detail, a small increase can be noticed for site 1.1 (Fig. 3C) in respect to site 1.1 (Fig. 3D), and for site 3.1 (Fig. 3C) to site 3.1 (Fig. 3D).

Late maize has significantly higher biomass than early maize (Table 3). Furthermore, the biomass changed significantly with site differences, where the highest biomass was found in the Coast site and the lowest in the North site (Table 3, Fig. 3). Time period (Table 3) nor treatment (Table 4) had a significant effect on the simulated biomass.

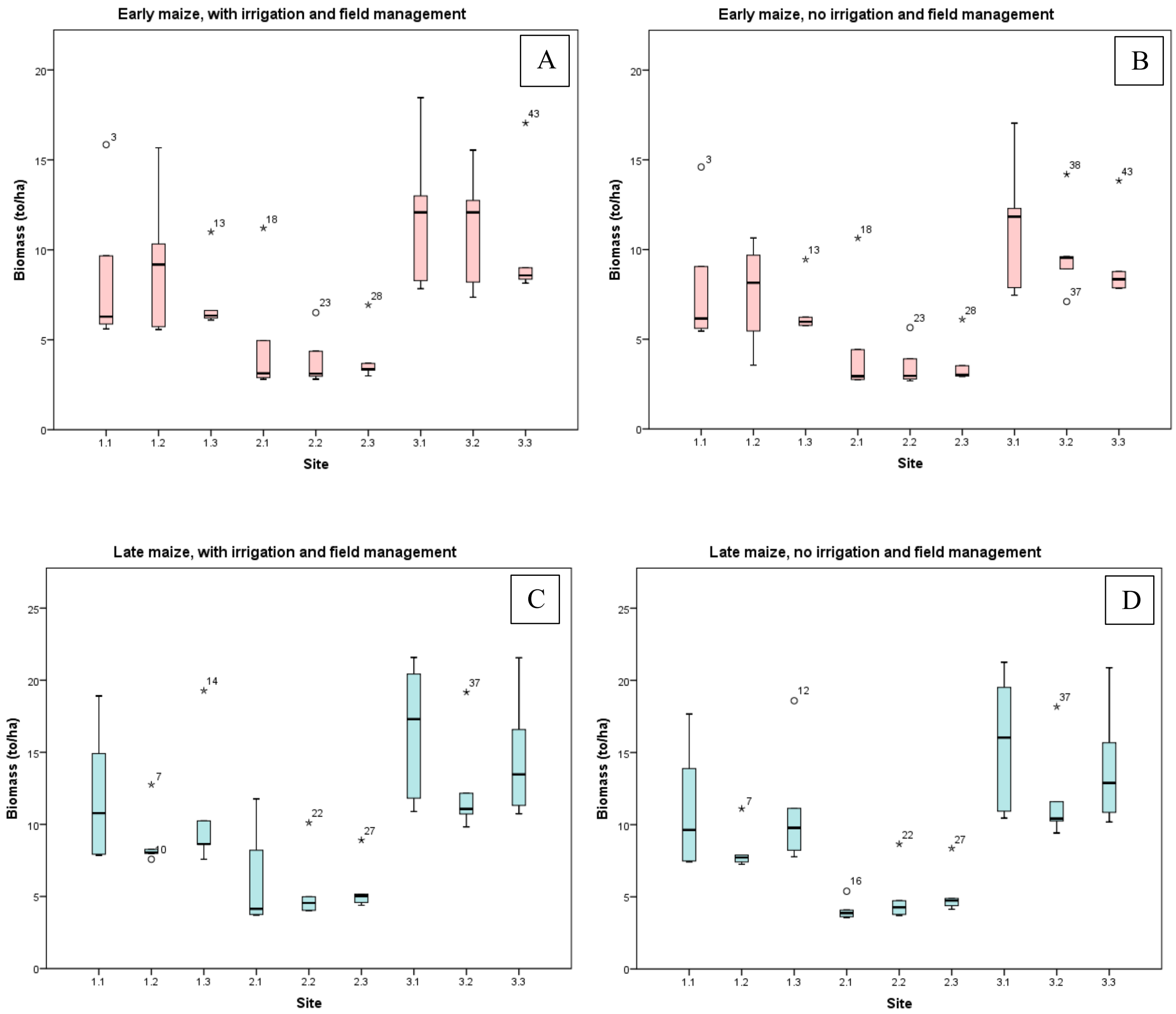

Figure 3. The boxes show first quartile, median and third quartile, and the whiskers (also called inner fences) show maximum and minimum. The outliers are identified with a circle, when they are not within the inner fences, and with a star, when they are extreme outliers and represent values which are triple the box's height. A) Boxplots of early maize with irrigation and field management. B) Boxplots of early maize without irrigation and field management. C) Boxplots of late maize with irrigation and field management. D) Boxplots of late maize without irrigation and field management. On the x axis, the three chosen sites, 1 corresponds to Central, 2 to North and 3 to Coast, simulated for three time periods (.1 → 1951-1955, .2 → 2015-2019, .3 → 2091-2095, future projections under the RCP8.5 scenario). On the y axis, biomass values expressed in to/ha.

Table 3. Two-way Anova test for biomass, yield and harvest DOY (as dependent variables) against type (early and late maize), site (Central, North, Coast) and time period (1951-1955, 2015-2019, 2091-2095)(all three as independent variables). The numbers represent the F value.

	Type	Site	Time period
Biomass	**7.21 ****	**8.37 ****	0.55 ns
Yield	2.21 ns	**9.61 ****	2.57 ns
Harvest DOY	**1152 *****	1.52 ns	**6.70 ***

*Note: Significances are indicated by the following key: * p < .05, **p < .01, ***p < .001, ns = not significant.*

Table 4. Two-way Anova test for biomass and yield (as dependent variables) against treatment (irrigation and field management), type (early and late maize) and the combination of treatment and type (all three as independent variables). The numbers represent the F value.

	Treatment	Type	Treatment x Type
Biomass	1.14 ns	**12.8 *****	0.01 ns
Yield	0.4 ns	2.6 ns	0.08 ns

*Note: Significances are indicated by the following key: * p < .05, **p < .01, ***p < .001, ns = not significant.*

4.1.2 Yields

The early maize yield for each site varies substantially during the three time periods under treatment conditions (Fig. 4A). In respect to Central, from a 1 to/ha yield average for the first period, there is a > 4 to/ha increase, and a projected final drop to < 1 to/ha in time period 3. All three periods for North show a yield value of 0. For Coast, from an average value of 4 to/ha, an increase occurs during the time range 2015-2019, and is projected to terminate with the same initial value for time period 3. The early maize yield simulated without treatment changes in each site, and under different time periods (Fig. 4B). Central shows a yield value under 2 to/ha during the three time ranges, with a slight increase from time 1 to time 2, and a projected drop in time 3, which corresponds to a future climate scenario characterized by higher temperatures (see Fig. 12). North has yield value of 0 over the three time ranges, while Coast shows a significant variability. During time period 1, the average yield reaches 8 to/ha, and it drastically drops to around 2 to/ha during the time period 2015-2019. A small increase to almost 4 to/ha is projected for time period 3. Overall, average yields under treatment are higher than average yields under treatment, for each of the three sites and time periods.

The late maize yield for each site varies substantially during the three time periods under treatment conditions (Fig. 4C). A significant average value is found in Central for the first time period, even though a drastic drop occurs in the time period 2. For the years 2091-2095, the late maize yield is projected to be lower than 2 to/ha. For North, in each time period, the average yield value corresponds to 0. In respect to Coast, initially the average yield is slightly beyond 8 to/ha, and it decreases during the time period 2 to less than 4 to/ha. Time period 3 is projected to produce a 4 to/ha yield. The late maize yield for each site varies substantially during the three time periods without any kind treatment conditions (Fig. 4D). Central is characterized by an initial, relatively low average yield of around 5 to/ha. A drop in terms of quantity occurs during time period 2, when the average value reaches almost 1 to/ha. A slight increase, but still lower than 2 to/ha, is projected during time period 3. North does not show any final yield over the three time periods. Coast, with an initial average value of around 8 to/ha for the first time period, reaches and is projected to reach respectively for time period 2 and 3, around 2 and 3 to/ha. Late maize yields resulting from non-included and included treatment do not seem to differ significantly (Fig. 4C/D).

Overall, a higher yield production can be observed for late maize in respect to early maize for all the three sites (Table 3), even though the statistical analysis does not show a significant correlation between type and yield due to the model simulation of one site (North) resulting in almost no yield production. The site differences have a significant impact on yield (Table 3). Neither treatment nor time period are significant for yield (Table 3 and 4).

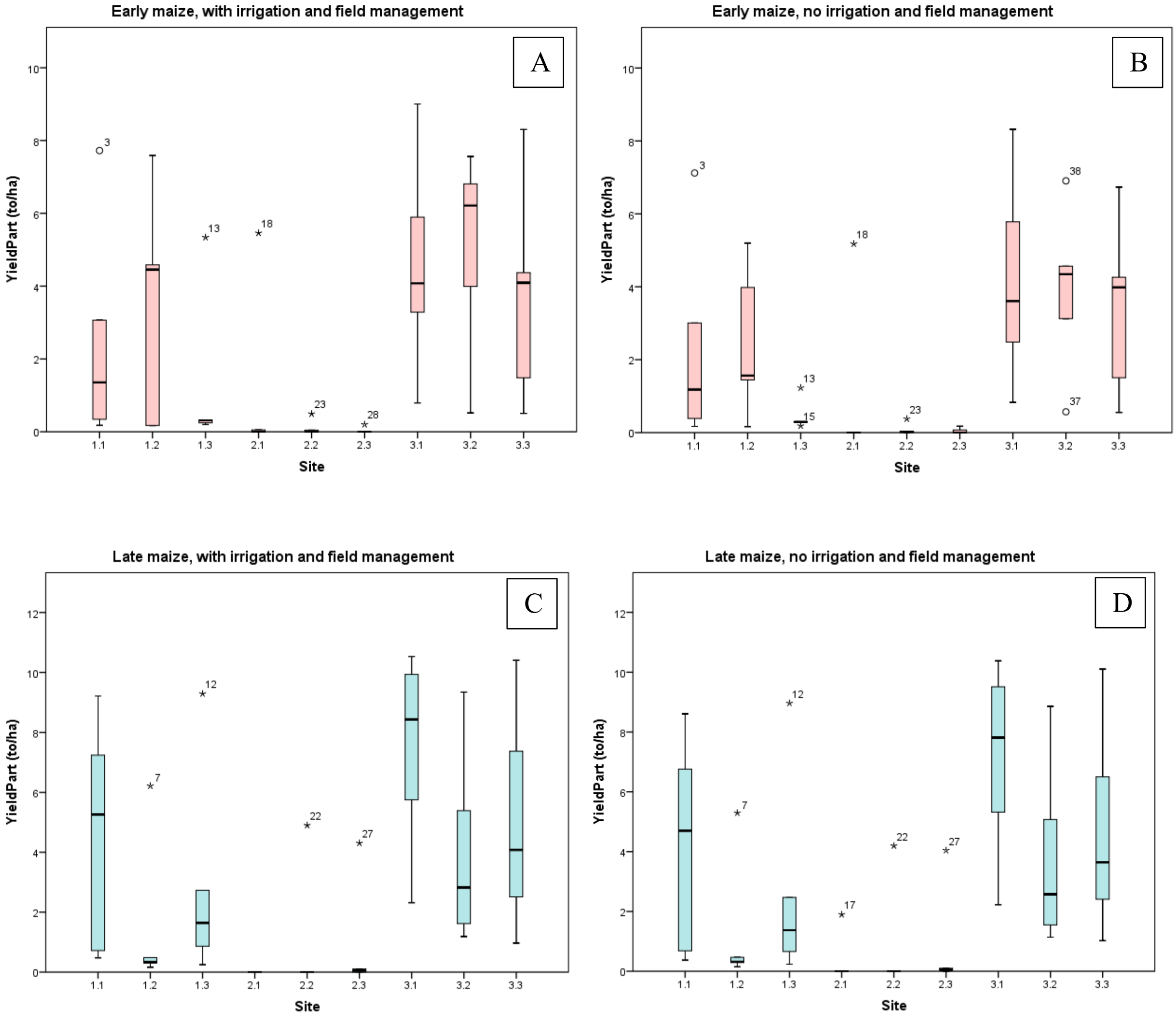

Figure 4. The boxes show first quartile, median and third quartile, and the whiskers (also called inner fences) show maximum and minimum. The outliers are identified with a circle, when they are not within the inner fences, and with a star, when they are extreme outliers and represent values which are triple the box's height. A) Boxplots of early maize with irrigation and field management. B) Boxplots of early maize without irrigation and field management. C) Boxplots of late maize with irrigation and field management. D) Boxplots of late maize without irrigation and field management. On the x axis, the three chosen sites, 1 corresponds to Central, 2 to North and 3 to Coast, simulated for three time periods (.1 → 1951-1955, .2 → 2015-2019, .3 → 2091-2095, future projections under the RCP8.5 scenario). On the y axis, yield values expressed in to/ha.

4.2 Maize response to temperature, evapotranspiration and precipitation

The number of days with temperature above 30°C during early and late maize growth is projected to gradually increase under the RCP8.5 scenario for North and Coast (Fig. 5). In North, a progressive increase of heat days is simulated during early maize growth. During late maize growth, a slight increase is projected from the year 2087. Central does not show any trend, while Coast shows a progressive increase for early maize from around 2010. During late maize, only a very small increase is visible in the last time period. The number of days below 8°C during early and maize growth are none. Therefore, it does not result significant (Appendix, Fig. A1).

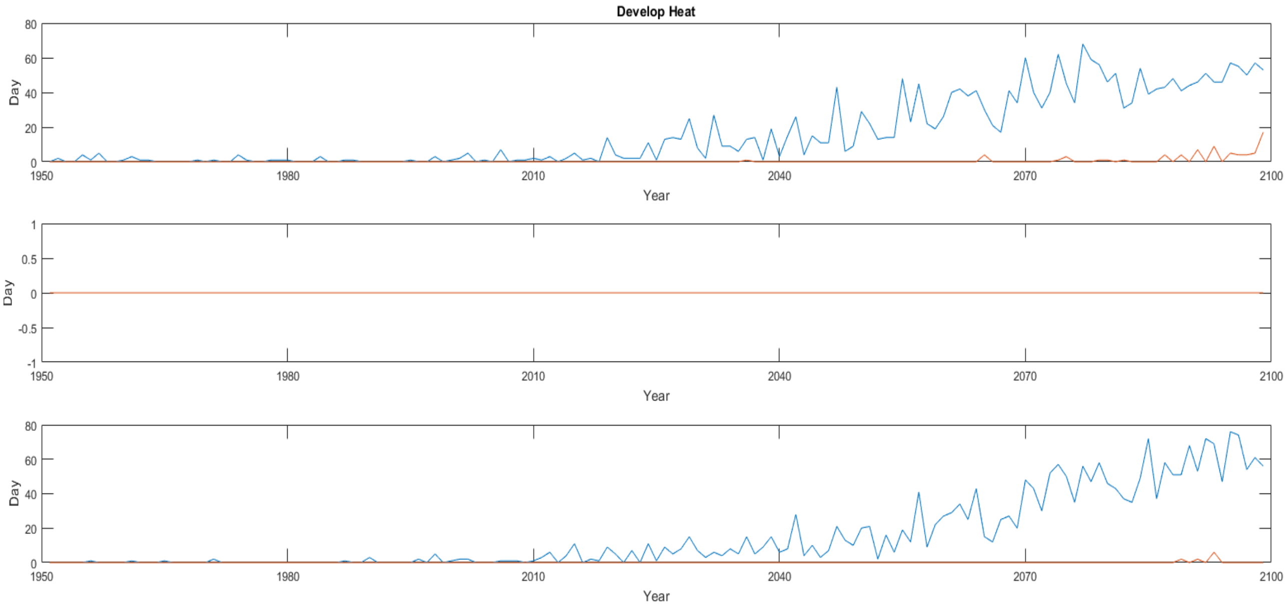

Figure 5. Number of days with temperature above 30°C during early (blue line) and late (orange line) maize growth for each year ranging from 1951 to 2100 under the RCP8.5 scenario. The first graph represents the North site, the second graph the Central site and the third one, the Coast site.

The day of the year (DOY) during which the flowering and maturity stage starts for early and late maize is projected to vary during the years (Fig. 6). In respect to early maize (blue line), in all the simulated sites, the start flowering day is projected to progressively begin a few days earlier as years advance. This earlier-trend is particularly pronounced for Central, in which early maize's flowering stage is projected to start almost 20 days earlier compared to the initial starting date. The same trend is observed for late maize in all sites, with the Central being the one with the most accentuated early-start flowering trend (around 20 days earlier compared to the initial starting date).

The maturity stage is projected to be reached earlier by both early and late maize. Considering early maize, North shows a very slight change for which maturity starts earlier. By 2100, it is projected to start around 5 to 6 days earlier. The variation is more pronounced for Central, representing a 40 days earlier start by 2100, while in Coast is projected to be almost unvaried (just a few days difference by 2100). In respect to late maize, it varies its maturity day by 2 to 3 days in the first location. In Central, it is projected to reach around a 30 days early maturity start by 2100 in comparison to 2050. Coast shows a 10 days early maturity start by 2100.

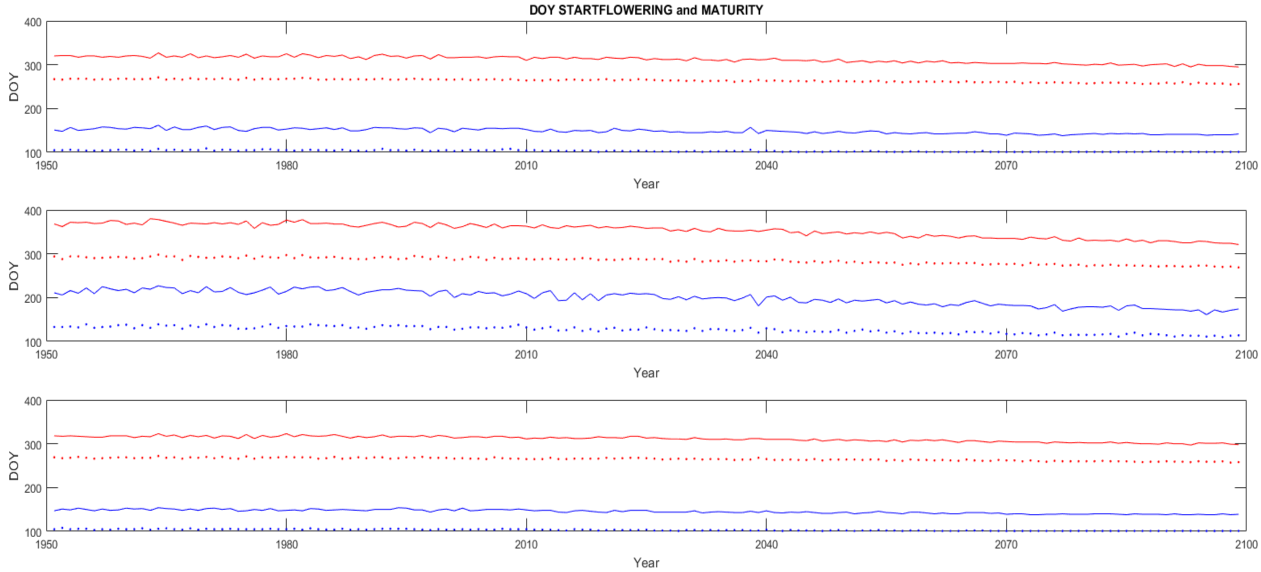

Figure 6. Day of the year (DOY) during which the flowering stage (dotted line) and maturity (continued line) starts for early (blue line) and late (red line) maize, for each year ranging from 1951 to 2100 under the RCP8.5 scenario. The first graph represents the North site, the second graph the Central site and the third one, the Coast site.

Evapotranspiration trends during early and late maize growth (from sowing to maturity) in each site are not projected to vary substantially (Fig. 7). All sites show a continuous, steady intervariability of values during a future climate change scenario.

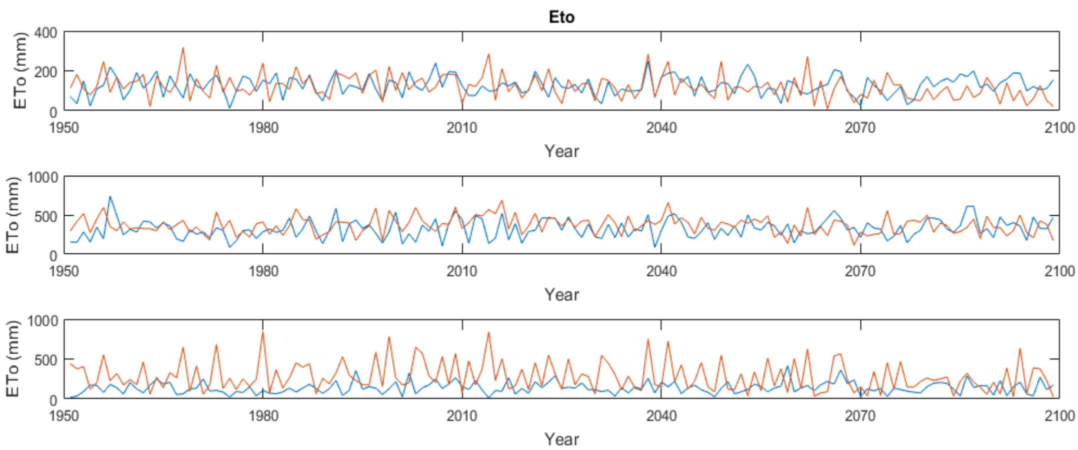

Figure 7. Evapotranspiration (in mm) trends during early (blue line) and late (orange line) maize growth (from sowing to maturity), for each year ranging from 1951 to 2100 under RCP8.5 scenario. The first graph represents the North site, the second graph the Central site and the third one, the Coast site.

Precipitation trends during early and late maize growth (from sowing to maturity) are projected to vary during a future climate scenario (Fig. 8). Overall, the rainfall trends do not substantially vary during early and late maize growth for North and Coast. However, during both early and late maize growth, a visible, progressive precipitation decrease is observed from the year 2000 and projected to continuously decrease until 2100 in Central.

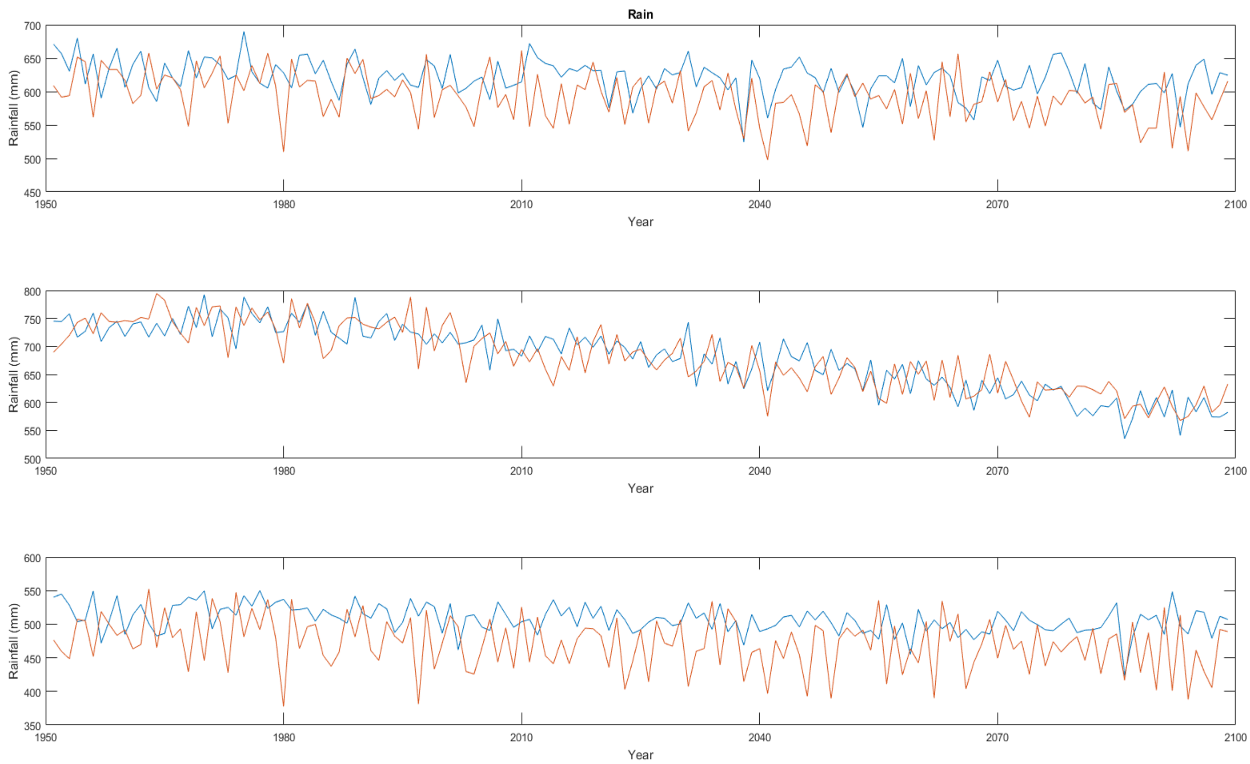

Figure 8. Rainfall (in mm) trends during early (blue line) and late (orange line) maize growth (from sowing to maturity), for each year ranging from 1951 to 2100 under RCP8.5 scenario. The first graph represents the North site, the second graph the Central site and the third one, the Coast site.

A few days are projected to be above 40°C during the crop's flowering (Fig. 9A). During late maize growth, none are projected, while during early maize growth a few are projected only in two sites. The North is projected to have a few days above 40°C between 2094 and 2098. Coast is projected to have a few days above 40°C during flowering between 2092 and 2094. Days below a 10°C air temperature during the crop's flowering, in early and late maize growth, are only projected in Central (Fig. 9B). Both early and late do not encounter any in North and Coast. In Central, during early maize growth, days below 10°C have been observed during flowering from 1951, and are projected in climate future scenarios until 2047. Afterwards, they are only projected to single years. In respect to late maize, a high variability of cold days (below 10°C) have been observed from 1951, and are projected to stop by 2041.

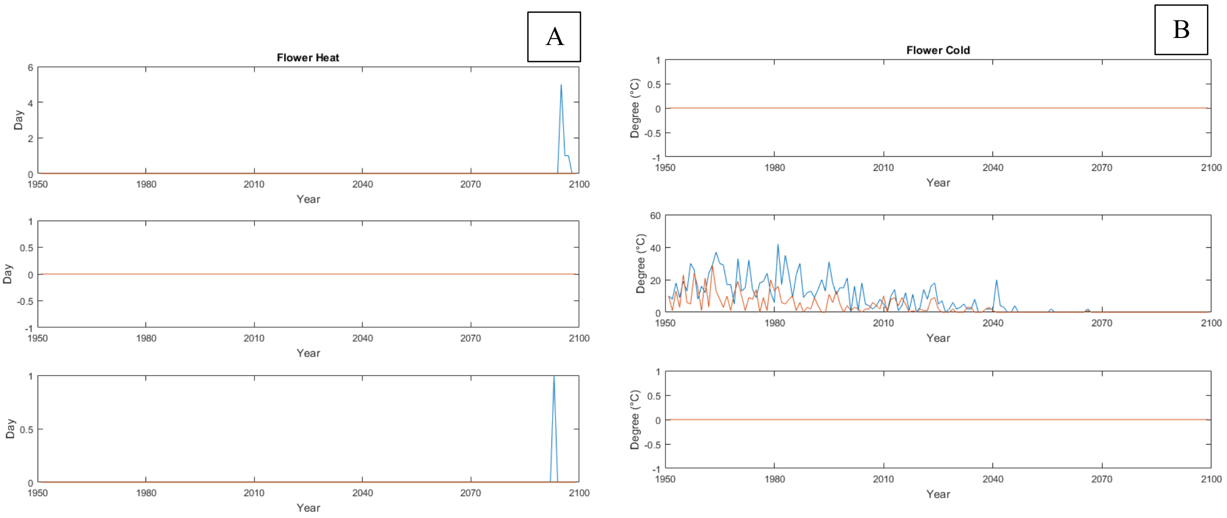

Figure 9. A) Days during which the air temperature is above 40°C (condition for which pollination starts to fail due to heat stress) during the crop's flowering, in early (blue line) and late (orange line) maize growth, for each year ranging from 1951 to 2100 under RCP8.5 scenario. The first graph represents the North site, the second graph the Central site and the third one, the Coast site. B) Days during which the air temperature is below 10°C (condition for which pollination starts to fail due to cold stress) during the crop's flowering, in early (blue line) and late (orange line) maize growth, for each year ranging from 1951 to 2100 under RCP8.5 scenario. The first graph represents the North site, the second graph the Central site and the third one, the Coast site.

Temperature (in °C) during the entire growing cycle of early and late maize is projected to increase in a future climate scenario, in all sites (Fig. 10). Temperature values differ during the respective growth of early and late maize since they are planted in two different periods. In North, temperature is projected to increase by 4°C during both early and late maize growth by 2100. In respect to Central, temperature during both early and late simulations does not highly differ, only by 1°C or so. However, from 2030, it is projected to progressively increase by 5°C until 2100. Looking at Coast, a progressive temperature increase is projected during both early and late maize growth. For early maize, it is projected to increase by almost 3°C by 2100. It will reach almost 30°C. Considering late maize, a 3°C increase is projected, by reaching an average temperature of 27°C by 2100.

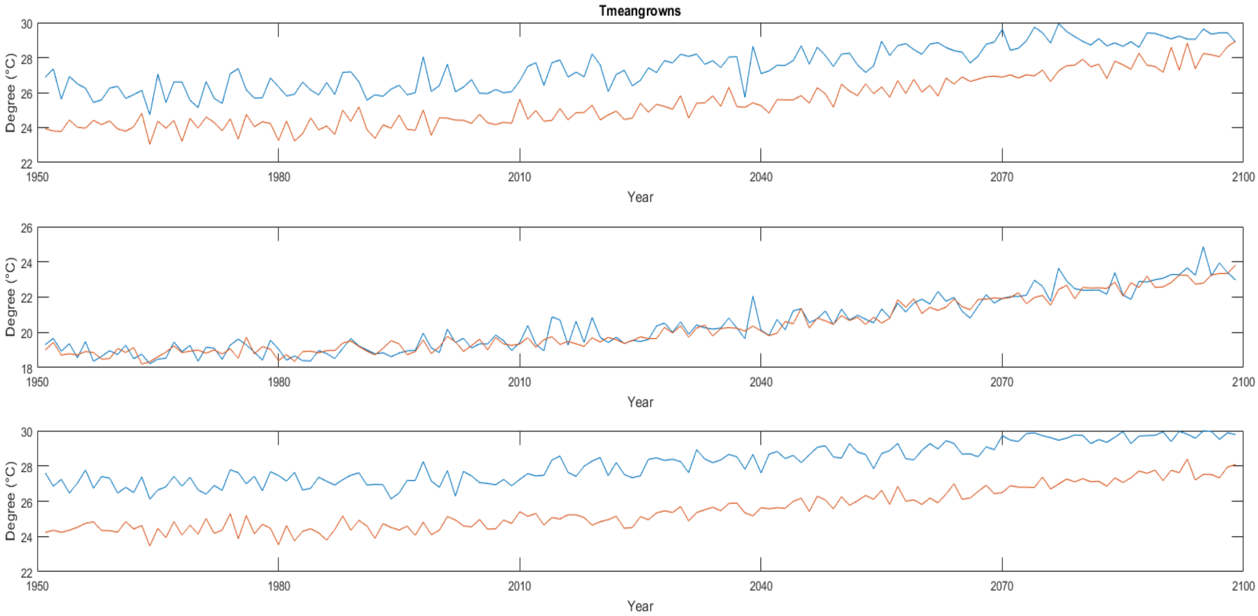

Figure 10. Temperature (in °C) during the growing period of early (blue line) and late (orange line) maize (from sowing to maturity), for each year ranging from 1951 to 2100 under RCP8.5 scenario. The first graph represents the North site, the second graph the Central site and the third one, the Coast site.

Temperatures during the entire maize growing cycle are projected to increase during the last time period, with type being highly significant (Table 4). Only three time periods were considered for the statistical analysis: 1951-1980, 2011-2040, 2071-2099. Time period has in fact a highly significant impact on temperature as it resulted from the ANOVA test (Table 5). The site has also a high significant impact on temperature, together with its interaction with type (Table 5).

Table 5. Two-way Anova test for Tmeangrowns (as dependent variables) against type (early and late), time period (each of 30 years; 1 comprehends 1951-1980, 2 comprehends 2011-2040, 3 comprehends 2071-2099), site (Central, North, Coast) and the interaction of type and site, all four as independent variables (non-significant interactions not shown). The numbers represent the F value.

	Type	**Time period**	**Site**	**Type x Site**
Tmeangrowns	**180.93 *****	**136.97 *****	**1991.23 *****	**72.85 *****

*Note: Significances are indicated by the following key: * p < .05, **p < .01, ***p < .001, ns = not significant.*

5 Discussion

5.1 Key findings

The results showed a relatively high late maize yield production, both under and without irrigation and field management, in a future climate change scenario. Early maize yields are projected to decrease in a future climate change scenario. In addition, during early and late maize growth, temperatures were projected to increase by 4°C in all three sites, whereas precipitation were projected to decrease only in the Central site. Evapotranspiration trends did not show any trend. Early and late maize flowering and maturity stages were projected to start earlier in a warmer climate, together with a higher number of days exceeding the developmental threshold of 30°C during early and late maize growth. Furthermore, during early maize flowering, days during which the air temperature is above 40°C are projected in Coast and North. Only in Central, days during which the air temperature in current climate is below 10°C during early and late maize flowering are projected to progressively decrease and disappear in a climate change scenario.

5.2 Kenya case

In Kenya, agriculture is mainly rain-fed and, consequently, is very dependent on precipitations. Kenya is characterized by two rainy seasons: from March to June (long), and from October to January (short). However, the precipitation amounts differ from area to area as reported by Amissah-Arthur et al. (2002). In fact, the highest are in the highlands in the western part, and the lowest in the northern and southern lowlands. Since rainfall amounts can be very low, and this condition can persist on a continuous temporal scale, these areas are the most subjected to droughts. The coastal zone is characterized by high precipitation amounts (Amissah-Arthur et al., 2002). In agricultural terms, these conditions get translated into favorable, and not, locations for agricultural production. Hence, the highlands and coastal zone are the areas with the highest cropping production and population rate. While the arid and semi-arid northern and southern regions are not suitable for agricultural cultivation. Therefore, the literature supports the results obtained which show the highest observed and projected yield production in Coast, and the lowest in the North (Fig. 4). However, the results for Central do not project as high yields as expected according to the literature. In this site, a progressive rainfall decrease is projected in a future climate change scenario (Fig. 8), accompanied with a decrease in biomass growth and yield production (Fig. 3 and 4). Similarly, Waha et al. (2013) observed maize yield reductions due to lower precipitation rates. Therefore, decreased rainfall can be an explanation, and cause, of lower maize yield (Fig. 4).

The North site encounters for biomass growth (Fig. 3), but not for yield production (Fig.4). The reason lies within its location. It is an area not suitable for agricultural production as Amissah-Arthur et al. (2002) also report.

Precipitation trends present a very high interannual variability induced by the so-called ENSO phenomenon. The large variation among years in biomass and yields explains the outliers (Fig. 3 and 4). It is characterized by a dual nature of events, el Niño (warming) and la Niña (cooling). With a 2 to 7 years occurrence, it initially takes place on the Peruvian coast with a water surface warming. However, from a local phenomenon, its impacts extend worldwide (Rojas et al, 2014). As literature supports, el Niño and la Niña cause major impacts in Kenya, which manifest through droughts and heavy rainfall, resulting in agricultural losses (Rojas et al, 2014; OCHA, 2016). However, a study by

Amissah-Arthur et al. (2002) shows that the impacts of the ENSO phenomenon vary from area to area in Kenya which induces a high variability and, at times, can represent a source of uncertainty.

Evapotranspiration is also a relevant aspect for maize growth (Djaman et al., 2013). It is the combination of the water that evaporates from the soil (evaporation) and from the crop (transpiration) (Blanc, 2012). Adequate levels of evapotranspiration result in high maize yields (Djaman et al., 2013). Evapotranspiration values show a high variability (Fig. 7), which is a typical feature of the region (Seneviratneet al., 2010). In this study, the results for the modelled evapotranspiration levels during early and late maize growing cycle do not show substantial present, and future, trends or possible changes (Fig. 7). However, it can be said that Central, located at 1635m of altitude, shows lower values in respect to the other two sites. This is related to an elevation factor since, according to Fisher et al. (2015), evapotranspiration and, consequently, moisture stress, have the tendency to be higher at low altitudes. Therefore, they suggest the adoption of drought tolerant varieties at low altitudes, and of non drought-tolerant varieties at higher elevations. Furthermore, an interesting aspect related to the Central site and elevation can be observed in Fig. 9. The North and Coast site are at low altitude which might be the reason for which days below 10°C during the early and late maize flowering stage have not been observed and projected (Fig. 9B), while days above 40°C during a future climate change scenario have been simulated during early maize flowering (Fig. 9A). On the other hand, the Central site is at 1635m, possible reason for which a significant number of days below 10°C during the early and late maize flowering stage (Fig. 9B) have been observed. A future trend shows their progressive decrease until their disappearance during a climate future scenario dominated by higher temperatures (Fig. 8).

Temperatures during early and late maize growth are projected to rise by around 4°C under the RCP8.5 scenario (Fig. 8), resulting in lower maize yields (Fig. 4). By comparing the average each site's final (both early and late) maize yield under the past and current scenarios to future projections, yields are evidently lower (Fig. 4) as well as biomass growth (Fig. 3). Anyhow, many studies, such as by Thornton et al. (2011) and Lobell et al. (2011), have shown maize yields decreases caused by higher temperatures. During early maize growth, temperatures are projected to reach 30°C in the North and Coast sites, conditions that challenge the crop's growth. In fact, even if maize as a plant can bear warm temperatures, 30°C represent the threshold for which, if crossed, production starts decreasing (Lobell et al., 2011). Another significant aspect is related to the start flowering and maturity DOY. As temperatures are projected to progressively increase, early and late maize flowering and maturity stages will be reached earlier (Fig. 6). Therefore, a higher amount of hot days during maize growth are projected to occur in a future climate change scenario, especially during early maize growth (Fig. 5). However, this trend seems to affect only the North and the Coast sites.

Temperature and precipitations can also be analyzed as a combined effect as many other studies have done. In this regard, Cairns et al. (2012) observed a negative maize growth and production induced by the coupled increased temperature and decreased rainfall. Therefore, this theory can prove the projected lower maize yields of this current study (Fig. 4) in combination to higher projected temperatures (Fig. 10) and decreased precipitation (Fig. 8) for the Central site. However, this explanation cannot be applied for the other two sites since they do not show significant future precipitation variations (Fig. 8), but only in terms of temperature (Fig. 10).

Studies have identified suitable soil profiles for maize growth (Du Plessis, 2003; FAO, n.d.). Considering the three sites and biomass growth (Fig. 3), the highest production occurred and is projected to occur in the Coast site whose soil texture is clay. If not too dense, it can represent a suitable soil type for maize growth (Du Plessis, 2003). According to Du Plessis (2003), the soil profile of sandy clay loam is one of the most adequate for maize growth. It characterizes the Central site, in which a relatively high maize growth has been observed and projected, but not as high as the Coast site (Fig. 3). The North site is covered by a low depth, sandy soil, feature that does not suit particularly maize growth according to Du Plessis (2003), and therefore results quite low in comparison to the other two sites (Fig. 3). According to the soil classification by FAO-Unesco (1974), the leptosol lithic type, which characterizes the North site, often contains relevant quantities of gravel. This feature negatively affects the maize's root development in the soil and, therefore, its overall development (Grewal et al., 1984). Furthermore, as Grewal et al. (1984) observed, gravels lead to a lower soil nutrient's content and water holding ability, which resulted in reduced rainfed maize yields.

Generally, irrigation systems and field management of different types are employed in the agricultural sector to enhance yield production. However, due to the lack of education and economic funds, they are rarely employed in the sub-Saharan Africa agriculture which is mainly rain-fed (Folberth et al., 2013). In this study, two types of simulations were run with and without treatment (irrigation and field management). Undoubtedly, the runs with treatment showed higher biomass values than the ones without (Fig. 3), but not of a significance difference. There is not a proper explanation for this since the literature highly supports irrigation measurements and field management, and observes positive yield enhancements (Bryan et al., 2013; Cairns et al., 2013). In a study, Mukhtar Iderawumi and Friday (2018) obtained successful results from employing weed management. However, this result suggests a higher maize production dependency on temperature rather than on precipitation. Otherwise, improved irrigation would have resulted in significantly higher maize yields.

5.3 Model limitation and improvements

Overall, AquaCrop is highlighted for its robustness and accuracy (Greaves and Wang, 2016). The crop model is relatively simple and intuitive. According to Ngetich et al. (2012), AquaCrop is very suitable for simulations in the SSA facing climate change scenarios, and for the formulation of adaptation strategies and management practices. This is enabled by its feature to simulate under irrigation and field management conditions, which allows the comparison of final yields with or without any kind of treatment. AquaCrop is suitable for the simulation of data directly collected from the field since it offers the possibility to insert very specific soil and crop features. However, in this study, a relevant limitation has been observed. Even though the literature does not provide any information about it, the 6.1 version of AquaCrop only simulates year by year. Thus, this feature makes it difficult to provide a complete overview of maize production in the long-run under climate change scenarios. Surely, a significant improvement could be done by enlarging the model's ability to simulate on a longer temporal scale. In fact, it is not too optimal to run manually, each at a time, all the simulations.

In addition, as another future improvement for this study, land cover and land use changes (LCLUC) should be included in the modelling frame. According to Moore et al. (2014), precipitation trends in East Africa are found to be influenced by LCLUC. Human induced changes in biophysical surface properties have impacts and cause alterations on different metereological scales. In this frame, it is significant to note this in relation the long-rain season. As a matter of fact, its alterations have been found to be partly induced by LCLUC (Moore et al., 2014). Therefore, according to Moore et al. (2014), LCLUC should not be excluded from agricultural projections, and can help in a more complete understanding of climate change impacts. However, due to their large spatial resolutions, GCMs are not able to capture this factor, while only some RCMs are able to since they operate on finer scales (Moore et al., 2014; Niu et al., 2018; Paeth et al., 2011).

5.4 Model support and food security

Despite high interannual variabilities, this study is enough to develop an impact assessment for future effects derived from climate change on agriculture. A projected future scenario dominated by higher temperatures and projected lower maize yields, at least for the early variety, will most likely lead to certain social implications. Even though there are manifold, this study only considers two.

Climate change is likely to lead to migrations (Barrios et al., 2006). Considering the future adverse effects of climate change on agriculture, and considering that most of the agricultural activities take place in rural areas, migrations towards urban areas are projected to occur on a higher frequency. Urban areas offer job positions in many other sectors beyond agriculture, therefore they represent a safer, and more attractive, choice (Marchiori et al., 2012). In addition, according to Marchiori et al. (2012), this step would lead to a second migration, outside of the country borders. Two dynamics are specific of the SSA urbanization trend. Currently, a significant fraction of the land is being converted for urban purposes, and the urbanization trend which takes place in the SSA results very chaotic (Moore et al., 2014; Myers and Murray, 2006). Therefore, considering these features, and a projected migration rate increase, adaptation strategies that can maintain a sufficient agricultural production are fundamental. In this way, a continuous, and higher, rural-urban migration could be mitigated.

Furthermore, considering the projected yield trends, food security will be adversely affected. However, in order to obtain a more complete assessment, information regarding the actual social side should be considered. For instance, how many people there are, and the age categories. How much food is actually needed in terms of quantity. How the political setting is, if the area is under conflict or not. The basic concept behind guaranteeing food security is that it needs to assure sufficient food and, especially, adequate nutrition which is at the base for a good health condition. The definition of food security (see section 2.2) includes its basic, four dimensions of availability, stability, access, and utilization (Schmidhuber and Tubiello, 2007). Briefly, the first refers to food availability, and its subdimensions of agro-climate and socio-economic factors on which agricultural production depends on. Stability refers to the singular person who is at an elevated risk of losing, either for a limited time or permanently, the resource to access to sufficient food. The access dimension is related to the actual access to a mean which can guarantee the acquisition of nutritious food (Schmidhuber and Tubiello, 2007). The last dimension comprehends all the aspects of nutrition. Therefore, not only in terms of quantity, but also quality of what the product contains and how is made from/with. There can be a sufficient amount of food, but if the quality is inadequate and affects the individual's health, then it is counter-productive. This brief excursus shows the complexity behind food security. This concept encompasses many spheres. Therefore, when considering food security, an interdisciplinary approach is needed.

5.5 Adaptation strategy

The results from this study show higher yields for the late maize variety, based on the sowing date, in comparison to the early maize variety (Fig. 4). Therefore, in a future climate change scenario, late planting maize varieties are more suitable for adaptation strategies in the three studied sites since they guarantee a relatively high yield production. However, the most suitable maize variety as adaptation strategy is highly dependent on the specific location for which it is addressed. In fact, the factors of temperature and precipitation need to be considered, and affect the choice of the variety. For this reason, the literature suggests both early and late maize varieties, both on a genetic and sowing date perspective, as possible adaptation strategy. For instance, Bello et al. (2012) propose early drought tolerant maize in opposition to late maize types. MacCarthy et al. (2018) observed lower yields due to the late maize planting. On the other hand, the literature also recommends late maize varieties (based on genetics, sowing date, or both) as adaptation strategies. In a study, Amissah-Arthur et al. (2002) suggested late planting (October) in Kenya. Another study set in Kenya by Wamari et al. (2007) suggests planting in May and June to enhance crop yields. It needs to be remarked that education is also essential when a new variety is introduced. For instance, a significant number of farmers in Kenya started employing early maize types after receiving an adequate level of on-topic education, with positive results (Mabonga, 2017). Differently, if the farmer does not know specific information regarding its planting and growth, the outcome will be negative (Opiyo et al., 2015). An adequate political, economic and social asset can facilitate the introduction of new varieties. Economic funds are especially significant since maize varieties are can be produced through genetic processing (Opiyo et al., 2015). However, varieties can also only depend on their sowing date.

6 Conclusion

This study was conducted to assess the effect of climate change on agriculture in the SSA using Kenya as a case study. Fur this purpose, the crop model AquaCrop, developed by FAO, was employed to model early and late sowing maize varieties under climate change scenario (RCP8.5) for the three time periods 1951-1955, 2015-2019, 2091-2095. The runs were executed both with and without treatment (irrigation and field management). Final modelled biomass and yield were obtained as result. In parallel, important temperature-dependent maize development thresholds were specifically analyzed. The results from AquaCrop showed lower early maize yields in a future climate change scenario, and relatively higher late maize yields. Nevertheless, a statistical test was performed and did not show a significant correlation between type (variety) and yield, but did show a significance for biomass and type (variety). This was due to the model simulation of one site (North) resulting in almost no yield production. Despite high interannual variabilities, AquaCrop model simulations covering 5 years are considered sufficient to develop an impact assessment for future effects derived from climate change on agriculture. However, as future improvement, enlarging the AquaCrop temporal simulation scale would be suitable, considering that the version 6.1 can only simulate year-by-year. In addition, for future studies, land cover and land use changes (LCLUC) should be included in the employed RCM, and by which the AquaCrop model would be forced with.

References

Abedinpour, M., A. Sarangi, T. Rajput, M. Singh, H. Pathak, and T. Ahmad. 2012. Performance evaluation of AquaCrop model for maize crop in a semi-arid environment. *Agricultural Water Management* 110: 55-66. doi:10.1016/j.agwat.2012.04.001.

Adnan, A., J. Jibrin, A. Kamara, B. Abdulrahman, A. Shaibu, and I. Garba. 2017. CERES–Maize Model for Determining the Optimum Planting Dates of Early Maturing Maize Varieties in Northern Nigeria. *Frontiers in Plant Science* 8. doi:10.3389/fpls.2017.01118.

Alexandratos, N., J. Bruinsma. 2012. World Agriculture towards 2030/2050: the 2012 Revision. Food and Agriculture Organization of the United Nations, Rome, pp. 147

Amissah-Arthur, A., S. Jagtap, and C. Rosenzweig. 2002. Spatio-temporal effects of El Niño events on rainfall and maize yield in Kenya. *International Journal of Climatology* 22: 1849-1860. doi:10.1002/joc.858.

Arnell, N., Hudson, D. A. and Jones, R. G. 2003. Climate change scenarios from a regional climate model: Estimating change in runoff in southern Africa. *Journal of Geophysical Research* 108. doi:10.1029/2002jd002782.

Asghar, A., A. Ali, W.H. Syed, M. Asif, T. Khaliq and A.A. Abid. 2010. Growth and yield of maize (Zea mays L.) cultivars affected by npk application in different proportion. *Pakistan Journal of Science* 62 (4): 211-216.

Barrios, S., L. Bertinelli, and E. Strobl. 2006. Climatic change and rural–urban migration: The case of sub-Saharan Africa. Journal of Urban Economics 60: 357-371. doi:10.1016/j.jue.2006.04.005.

Bassu, S., N. Brisson, J. Durand, K. Boote, J. Lizaso, J. Jones, C. Rosenzweig, and A. Ruane et al. 2014. How do various maize crop models vary in their responses to climate change factors?. *Global Change Biology* 20: 2301-2320. doi:10.1111/gcb.12520.

Bello, O. B., S. Y. Abdulmaliq, S. A. Ige, J. Mahamood, F. Oluleye, M. A. Azeez, M. S. Afolabi. 2012. Evaluation of Early and Late/Intermediate Maize Varieties for Grain Yield Potential and Adaptation to a Southern Guinea Savanna Agro-ecology of Nigeria. *International Journal of Plant Research 2012*, 2(2): 14-21. doi: 10.5923/j.plant.20120202.03

Blanc, E. 2012. The Impact of Climate Change on Crop Yields in Sub-Saharan Africa. *American Journal of Climate Change* 01: 1-13. doi:10.4236/ajcc.2012.11001.

Brouwer, C., K. Prins, M. Kay, and M. Heibloem. 2001. *Irrigation Methods*. Irrigation Water Management: training manual n°5. FAO Land and Water Development Division, Rome.

Bryan, E., C. Ringler, B. Okoba, C. Roncoli, S. Silvestri, and M. Herrero. 2013. Adapting agriculture to climate change in Kenya: Household strategies and determinants. *Journal of Environmental Management* 114: 26-35. doi:10.1016/j.jenvman.2012.10.036.

Cairns, J.E., J. Hellin, , K. Sonder, J.L. Araus, J.F. MacRobert, C. Thierfelder, and B. M. Prasanna. 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Security* 5 (3): 345-360. doi: 10.1007/s12571-013-0256-x

Cairns, J.E., K. Sonder, P.H. Zaidi, P.N. Verhulst, G. Mahuku, R. Babu, S.K. Nair, B. Das, B. Govaerts, M.T. Vinayan, Z. Rashid, J.J. Noor, P. Devi , F. san Vicente, and B.M. Prasanna. 2012. Chapter one-Maize production in a changing climate: Impacts, adaptation, and mitigation strategies. In *Advances in Agronomy* 114: 1-58. doi: 10.1016/B978-0-12-394275-3.00006-7

Çakir, R. 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Research* 89: 1-16. doi:10.1016/j.fcr.2004.01.005.

Cheruiyot, E., L. Mumera, L. Nakhone, and S. Mwonga. 2001. Rotational effects of grain legumes on maize performance in the Rift Valley Highlands of Kenya. *African Crop Science Journal 9*. doi:10.4314/acsj.v9i4.27588.

Chijioke, O.B., M. Haile, C. Waschkeit. 2011. Implication of Climate Change on Crop Yield and Food Accessibility in Sub-Saharan Africa. Interdisciplinary Term Paper. Bonn, Germany: University of Bonn.

Cooper, P., J. Dimes, K. Rao, B. Shapiro, B. Shiferaw, and S. Twomlow. 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change?. *Agriculture, Ecosystems & Environment* 126: 24-35. doi:10.1016/j.agee.2008.01.007.

CORDEX. (n.d). History. Retrieved 28 March 2019, from http://www.cordex.org/about/history/

Crafts-Brandner, S.J., M.E. Salvucci. 2002. Sensitivity of Photosynthesis in a C4 Plant, Maize, to Heat Stress. *PLANT PHYSIOLOGY* 129: 1773-1780. doi:10.1104/pp.002170.

Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther. 2013: Introduction. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Denton, F., T.J. Wilbanks, A.C. Abeysinghe, I. Burton, Q. Gao, M.C. Lemos, T. Masui, K.L. O'Brien, and K. Warner. 2014. Climate-resilient pathways: adaptation, mitigation, and sustainable development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131.

Dile, Y., L. Karlberg, M. Temesgen, and J. Rockström. 2013. The role of water harvesting to achieve sustainable agricultural intensification and resilience against water related shocks in sub-Saharan Africa. *Agriculture, Ecosystems & Environment* 181: 69-79. doi:10.1016/j.agee.2013.09.014.

Djaman, K., S. Irmak, W. R. Rathje, D. L. Martin and D. E. Eisenhauer. 2013. Maize Evapotranspiration, Yield Production Functions, Biomass, Grain Yield, Harvest Index, and

Yield Response Factors under Full and Limited Irrigation. *Transactions of the ASABE* 56: 373-393. doi:10.13031/2013.42676.

Du Plessis, J.. 2003. Maize production. Department of Agriculture, Pretoria, South Africa, 34 pp.

Dupuis, I., and C. Dumas. 1990. Influence of Temperature Stress on in Vitro Fertilization and Heat Shock Protein Synthesis in Maize (Zea mays L.) Reproductive Tissues. *PLANT PHYSIOLOGY* 94: 665-670. doi:10.1104/pp.94.2.665.

FAO and ECA. 2018. Regional Overview of Food Security and Nutrition. Addressing the threat from climate variability and extremes for food security and nutrition. Accra. 116 pp.

FAO-Unesco. 1974. Soil map of the world, 1 : 5 000 000. Unesco, Paris.

FAO. (n.d). Maize. Retrieved 27 March 2019, from http://www.fao.org/land-water/databases-and-software/crop-information/maize/en/.

FAO. (n.d). What is AquaCrop. Retrieved 26 March 2019, from http://www.fao.org/aquacrop/overview/whatisaquacrop/en/.

FAO. 1996. Rome Declaration on World Food Security and World Food Summit Plan of Action.

FAO. 2015. Agroforestry definition. Retrieved 6 May 2019, from http://www.fao.org/forestry/agroforestry/80338/en/.

FAOSTAT. 2017. Crops. Retrieved 26 March 2019, from http://www.fao.org/faostat/en/#data/QC.

Farahani, H., G. Izzi, and T. Oweis. 2009. Parameterization and Evaluation of the AquaCrop Model for Full and Deficit Irrigated Cotton. *Agronomy Journal* 101: 469. doi:10.2134/agronj2008.0182s.

Feser, F., B. Rockel, H. von Storch, J. Winterfeldt, and M. Zahn. 2011. Regional Climate Models Add Value to Global Model Data: A Review and Selected Examples. *Bulletin of the American Meteorological Society* 92: 1181-1192. doi:10.1175/2011bams3061.1.

Fisher, M., T. Abate, R. Lunduka, W. Asnake, Y. Alemayehu, and R. Madulu. 2015. Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in eastern and southern Africa. *Climatic Change* 133: 283-299. doi:10.1007/s10584-015-1459-2.

Folberth, C., H. Yang, T. Gaiser, K. Abbaspour, and R. Schulin. 2013. Modeling maize yield responses to improvement in nutrient, water and cultivar inputs in sub-Saharan Africa. *Agricultural Systems* 119: 22-34. doi:10.1016/j.agsy.2013.04.002.

Giorgi, F., C. Jones, and G.R. Asrar. 2009. Addressing climate information needs at the regional level- the CORDEX framework. *WMO Bulletin*, 58 (3): 175-183.

Greaves, G. and Y. Wang. 2016. Assessment of FAO AquaCrop Model for Simulating Maize Growth and Productivity under Deficit Irrigation in a Tropical Environment. *Water*, 8(12): 557. doi:10.3390/w8120557

Grewal, S.S., K. Singh and S. Dyal. 1984. Soil profile gravel concentration and its effect on rainfed crop yields. *Plant and soil* 81: 75-83.

Hachigonta, S., G.C. Nelson, T.S. Thomas, and L.M. Sibanda. 2013. *Southern African agriculture and climate change: A comprehensive analysis*. International Food Policy Research Institute (IFPRI). Washington D.C. doi: 10.2499/9780896292086

Hallauer, A.R., M.J. Carena, and J.B. Miranda Filho. 2010. Preface. In *Quantitative genetics in maize breeding*. Springer science & business media. pp. 2-7.

Hertel, T. and U. Baldos. 2016. Population and incomes as drivers of climate change. In *Global Change and the Challenges of Sustainably Feeding a Growing Planet*. pp. 13-26. Springer International Publishing AG.

Holden, S.T., and M. Fisher. 2015. Can Adoption of Improved Maize Varieties Help Smallholder Farmers Adapt to Drought? Evidence from Malawi. Norwegian University of Life Sciences, Centre for Land Tenure Studies. CLTS Working Papers 1/15.

Hu, Y., Batunacun, L. Zhen, and D. Zhuang. 2019. Assessment of Land-Use and Land-Cover Change in Guangxi, China. *Scientific Reports* 9. doi:10.1038/s41598-019-38487-w.

Iken, J., and N. Amusa. 2004. Maize research and production in Nigeria. *African Journal of Biotechnology* 3: 302-307. doi:10.5897/ajb2004.000-2056.

IPCC. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 976pp.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC. 2014a. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

IPCC. 2014b. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2014c. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Karunaratne, A., S. Azam-Ali, G. Izzi, and P. Steduto. 2011. Calibration and validation of Fao-Aquacrop model for irrigated and water deficient Bambara groundnut. *Experimental Agriculture* 47: 509-527. doi:10.1017/s0014479711000111.

Kidane, W., M. Maetz and P. Dardel. 2006. Food security and agricultural development in sub-Saharan Africa. Building a case for more public support. Main report. FAO, Rome, Italy, pp.104.

Klopfenstein, T., G. Erickson, and L. Berger. 2013. Maize is a critically important source of food, feed, energy and forage in the USA. *Field Crops Research* 153: 5-11. doi:10.1016/j.fcr.2012.11.006.

Kori, S. M., C. Soothar, A.L. Qureshi and S.H. Ashrafani. 2017. Effect of different irrigation methods on water use efficiency and yield of maize crop. *Pakistan journal of agriculture, agricultural engineering & veterinary sciences 33(1): 54-65.*

Leng, G., and M. Huang. 2017. Crop yield response to climate change varies with crop spatial distribution pattern. *Scientific Reports* 7. doi:10.1038/s41598-017-01599-2.

Lennard, C., G. Nikulin, A. Dosio, and W. Moufouma-Okia. 2018. On the need for regional climate information over Africa under varying levels of global warming. *Environmental Research Letters* 13: 060401. doi:10.1088/1748-9326/aab2b4.

Liu, J., S. Fritz, C. van Wesenbeeck, M. Fuchs, L. You, M. Obersteiner, and H. Yang. 2008. A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change. *Global and Planetary Change* 64: 222-235. doi:10.1016/j.gloplacha.2008.09.007.

Lobell, D., M. Bänziger, C. Magorokosho, and B. Vivek. 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change* 1: 42-45. doi:10.1038/nclimate1043.

Mabonga, E.S. 2017. Effects of Climate Variability on Maize Yield in Matungulu West, Machakos County Kenya. Research project, Nairobi, Kenya: Kenyatta University.

MacCarthy, D., S. Adiku, B. Freduah, A. Kamara, S. Narh, and A. Abdulai. 2017. Evaluating maize yield variability and gaps in two agroecologies in northern Ghana using a crop simulation model. *South African Journal of Plant and Soil* 35: 137-147. doi:10.1080/02571862.2017.1354407.

Marchiori, L., J. Maystadt, and I. Schumacher. 2012. The impact of weather anomalies on migration in sub-Saharan Africa. Journal of Environmental Economics and Management 63: 355-374. doi:10.1016/j.jeem.2012.02.001.

Mati, B. 2000. The influence of climate change on maize production in the semi-humid–semi-arid areas of Kenya. *Journal of Arid Environments* 46: 333-344. doi:10.1006/jare.2000.0699.

McDonald, J.H. 2014. Handbook of Biological Statistics, 3rd ed. Sparky House Publishing, Baltimore, Maryland

McKevith, B. 2004. Nutritional aspects of cereals. *Nutrition Bulletin* 29: 111-142. doi:10.1111/j.1467-3010.2004.00418.x.

Mehdi Dahmardeh. 2012. Effects of sowing date on the growth and yield of maize cultivars (Zea mays L.) and the growth temperature requirements. *AFRICAN JOURNAL OF BIOTECHNOLOGY* 11. doi:10.5897/ajb12.201.

Moore, N., J. Andresen, B. Lofgren, B. Pijanowski, and D. Kim. 2014. Projected land-cover change effects on East African rainfall under climate change. International Journal of Climatology 35: 1772-1783. doi:10.1002/joc.4117.

Morris, M. L. 2001. Assessing the benefits of international maize breeding research: an overview of the global maize impacts study. In *CIMMYT 1999–2000 World Maize Facts and Trends. Meeting World Maize Needs: Technological Opportunities and Priorities for the Public Sector, part 2, pp.25-33*. Mexico City, D.F: CIMMYT.

Mukhtar Iderawumi, A. and C.E. Friday. 2018. Characteristics Effects of Weed on Growth Performance and Yield of Maize (Zea Mays). *Biomedical Journal of Scientific & Technical Research* 7. doi:10.26717/bjstr.2018.07.001495.

Myers, G., and M. Murray. 2006. Introduction: Situating Contemporary Cities in Africa. In *Cities in Contemporary Africa*, pp. 1-30. New York: Palgrave.

Ngetich, K. F., D. Raes, C. A. Shisanya, J. Mugwe, M. Mucheru-Muna, D. N. Mugendi, J. Diels. 2012. Calibration and validation of AquaCrop model for maize in sub-humid and semi-arid regions of central highlands of Kenya. *Proceedings of the Conference of RUFORUM Third Biennial Conference, Entebbe, Uganda*: 24-28.

Niang, I., O.C. Ruppel, M.A. Abdrabo, A. Essel, C. Lennard, J. Padgham and P. Urquhart. 2014. Africa. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

Nikulin, G., C. Jones, F. Giorgi, G. Asrar, M. Büchner, R. Cerezo-Mota, O. Christensen, and M. Déqué et al. 2012. Precipitation Climatology in an Ensemble of CORDEX-Africa Regional Climate Simulations. *Journal of Climate* 25: 6057-6078. doi:10.1175/jcli-d-11-00375.1.

Niu, X., J. Tang, S. Wang, and C. Fu. 2018. Impact of future land use and land cover change on temperature projections over East Asia. Climate Dynamics. doi:10.1007/s00382-018-4525-4.

OCHA. 2016. Overview of el Niño response in East and Southern Africa. Briefing note, 12 pp.

OECD/FAO. 2016. *OECD-FAO Agricultural Outlook 2016-2025 Special focus: sub-Saharan Africa*. Paris: OECD Publishing.

Ojeda-Bustamante, W., E. Sifuentes-Ibarra, D. Slack, and M. Carrillo. 2004. Generalization of irrigation scheduling parameters using the growing degree days concept: application to a potato crop. *Irrigation and Drainage* 53: 251-261. doi:10.1002/ird.134.

Opiyo, F., O. Wasonga, M. Nyangito, J. Schilling, and R. Munang. 2015. Drought Adaptation and Coping Strategies Among the Turkana Pastoralists of Northern Kenya. *International Journal of Disaster Risk Science* 6: 295-309. doi:10.1007/s13753-015-0063-4.

Orlowsky, B., and S. Seneviratne. 2011. Global changes in extreme events: regional and seasonal dimension. *Climatic Change* 110: 669-696. doi:10.1007/s10584-011-0122-9.

Oseni, G., and P. Winters. 2009. Rural nonfarm activities and agricultural crop production in Nigeria. *Agricultural Economics* 40: 189-201. doi:10.1111/j.1574-0862.2009.00369.x.

Paeth, H., N. Hall, M. Gaertner, M. Alonso, S. Moumouni, J. Polcher, P. Ruti, and A. Fink et al. 2011. Progress in regional downscaling of west African precipitation. *Atmospheric Science Letters* 12: 75-82. doi:10.1002/asl.306.

Pereira, L. 2017. Climate Change Impacts on Agriculture across Africa. *Oxford Research Encyclopedia of Environmental Science*. doi:10.1093/acrefore/9780199389414.013.292.

Raes, D. 2017. *AquaCrop training handbook I. Understanding AquaCrop*. Rome: FAO.

Ramirez-Cabral, N., L. Kumar, and F. Shabani. 2017. Global alterations in areas of suitability for maize production from climate change and using a mechanistic species distribution model (CLIMEX). *Scientific Reports* 7. doi:10.1038/s41598-017-05804-0.

Ranum, P., J. Peña-Rosas, and M. Garcia-Casal. 2014. Global maize production, utilization, and consumption. *Annals of the New York Academy of Sciences* 1312: 105-112. doi:10.1111/nyas.12396.

Rivington, M., and J. Koo. 2010. Report on the meta-analysis of crop modelling for climate change and food security survey. Climate Change, Agriculture and Food Security Challenge Program (CCAFS), Copenhagen, Denmark, 70 pp.

Rojas, O. E., Y. Li, R. Cumani, and Food and Agriculture Organization of the United Nations. 2014. Understanding the drought impact of El Niño on the global agricultural areas: an assessment using FAO's Agricultural Stress Index (ASI). FAO, Rome, Italy, 41 pp.

Rouf Shah, T., K. Prasad, and P. Kumar. 2016. Maize-A potential source of human nutrition and health: A review. *Cogent Food & Agriculture* 2. doi:10.1080/23311932.2016.1166995.

Rowell, D. 2011. Sources of uncertainty in future changes in local precipitation. *Climate Dynamics* 39: 1929-1950. doi:10.1007/s00382-011-1210-2.

Schlenker, W., and D. Lobell. 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters* 5: 014010. doi:10.1088/1748-9326/5/1/014010.

Schmidhuber, J. and F.N. Tubiello. 2007. Global food security under climate change. *PNAS 104 (50):* 19703-19708. https://doi.org/10.1073/pnas.0701976104

Seneviratne, S., T. Corti, E. Davin, M. Hirschi, E. Jaeger, I. Lehner, B. Orlowsky, and A. Teuling. 2010. Investigating soil moisture–climate interactions in a changing climate: A review. Earth-Science Reviews 99: 125-161. doi:10.1016/j.earscirev.2010.02.004.

Serdeczny, O., S. Adams, F. Baarsch, D. Coumou, A. Robinson, W. Hare, M. Schaeffer, and M. Perrette et al. 2016. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change* 17: 1585-1600. doi:10.1007/s10113-015-0910-2.

Shiferaw, B., B. Prasanna, J. Hellin, and M. Bänziger. 2011. Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Security* 3: 307-327. doi:10.1007/s12571-011-0140-5.

Soil metadata catalogue. (n.d). Soil and Terrain Database for Kenya (KENSOTER), version 2.0. Retrieved 20 March 2019, from https://data.isric.org/geonetwork/srv/ita/catalog.search#/metadata/73e27136-9efe-49e4-af35-fd98b841d467

Steduto, P., T.C. Hsiao, E. Fereres, and D. Raes. 2012. Crop yield response to water. FAO, irrigation and drainage paper 66, Rome, Italy, 500 pp.

Tao, F., M. Yokozawa, and Z. Zhang. 2009. Modelling the impacts of weather and climate variability on crop productivity over a large area: A new process-based model development, optimization, and uncertainties analysis. *Agricultural and Forest Meteorology* 149: 831-850. doi:10.1016/j.agrformet.2008.11.004.

ten Berge, H., R. Hijbeek, M. van Loon, J. Rurinda, K. Tesfaye, S. Zingore, P. Craufurd, and J. van Heerwaarden et al. 2019. Maize crop nutrient input requirements for food security in sub-Saharan Africa. *Global Food Security* 23: 9-21. doi:10.1016/j.gfs.2019.02.001.

Tesfaye, K., S. Gbegbelegbe, J. Cairns, B. Shiferaw, B. Prasanna, K. Sonder, K. Boote, and D. Makumbi et al. 2015. Maize systems under climate change in sub-Saharan Africa. *International Journal of Climate Change Strategies and Management* 7: 247-271. doi:10.1108/ijccsm-01-2014-0005.

Thornton, P.K., P.G. Jones, P.J. Ericksen and A.J. Challinor. 2011. Agriculture and food systems in sub-Saharan Africa in a 4 °C? world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369:117–136. doi:10.1098/rsta. 2010.0246

UNFPA. 2011. *Population Dynamics in the LDCs: Challenges and Opportunities for Development and Poverty Reduction*. New York: United Nations Population Fund (UNFPA).

USDA. 1987. Module 3-USDA textural soil classification study guide. In *soil mechanics level I,* USDA, pp.1-48.

Van Ittersum, M.K., L.G. van Bussel, and J. Wolf. 2016. Can sub-Saharan Africa feed itself? *PNAS* 113(52):14964–14969. doi: 10.1073/pnas.1610359113

Waha, K., C. Müller, and S. Rolinski. 2013. Separate and combined effects of temperature and precipitation change on maize yields in sub-Saharan Africa for mid- to late-21st century. *Global and Planetary Change* 106: 1-12. doi:10.1016/j.gloplacha.2013.02.009.

Wamari, J., S. Isaya, L. Kheng, J. Miriti, and E. Obutiati. 2007. Use of Aquacrop Model to Predict Maize Yields under varying Rainfall and Temperature in a Semi-Arid Environment in Kenya. *Journal of Meteorology and Related Sciences* 6: 26-35. doi:10.20987/jmrs.08.2012.603.

Welborn, L. 2018. Africa and climate change. Projecting vulnerability and adaptive capacity. Institute for Security Studies, Africa report 14, 23pp.

World bank (n.d). LAC Equity Lab: Poverty. Retrieved 24 April 2019, from http://www.worldbank.org/en/topic/poverty/lac-equity-lab1/poverty.

World bank. (n.d). Sub-Saharan Africa. Retrieved 24 April 2019, from https://data.worldbank.org/region/sub-saharan-africa

World Food Summit 13-17 November 1996. FAO, Rome.

Yavaş, I., A. Ünay. 2015. Response of Maize to Temperature, Carbon Dioxide and Irrigation Levels under the Conditions of Greenhouse. *Journal of Agricultural Faculty of Gaziosmanpasa University*, 32 (3):110-118. doi:10.13002/jafag805

Appendix

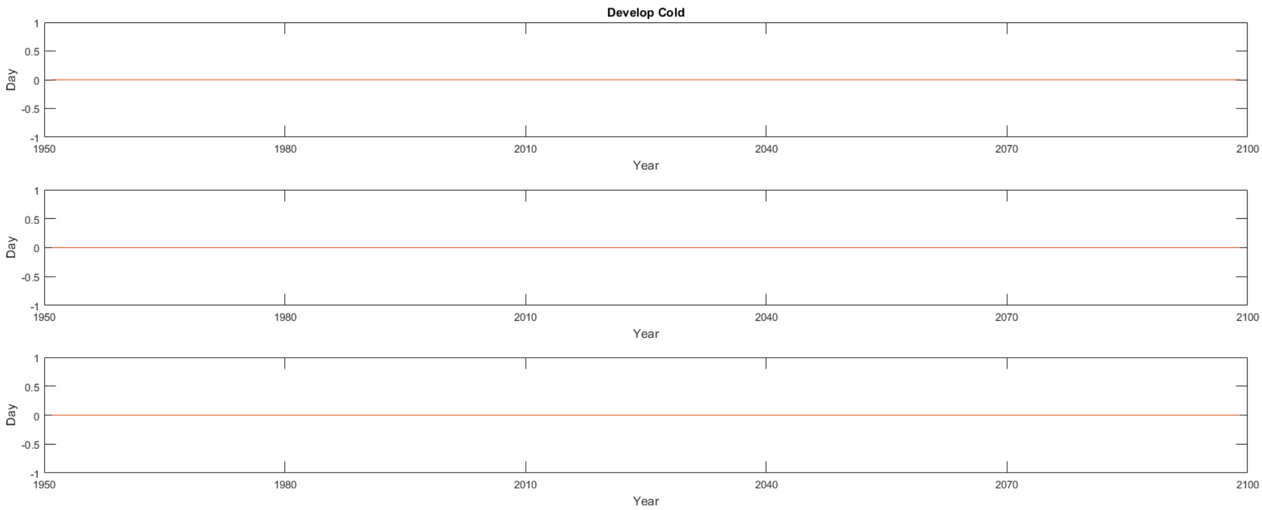

Figure A1. Number of days below 8°C during early (blue line) and late (orange line) maize growth for each year ranging from 1951 to 2100 under RCP8.5 scenario. The first graph represents the North site, the second graph the Central site and the third one, the Coast site. The two lines overlap since during both early and late maize growth days below 8°C are not projected to occur.