Chapter

Impact of Climate Change on Maize and Pigeonpea Yields in Semi-Arid Kenya

Kizito Musundi Kwena, G.N. Karuku, F.O. Ayuke and A.O. Esilaba

Abstract

The objective of this study was to assess the impact of climate change on intercrops of maize and improved pigeonpea varieties developed. Future climate data for Katumani were downscaled from the National Meteorological Research Centre (CNRM) and Commonwealth Scientific and Industrial Research Organization (CSIRO) climate models using the Statistical Downscaling Model (SDSM) version 4.2. Both models predicted that Katumani will be warmer by 2°C and wetter by 11% by 2100. Agricultural Production Systems Simulator (APSIM) model version 7.3 was used to assess the impact of both increase in temperature and rainfall on maize and pigeonpea yield in Katumani. Maize crop will increase by 141–-150% and 10–-23 % in 2050 and 2100, respectively. Intercropping maize with pigeonpea will give mixed maize yield results. Pigeonpea yields will decline by 10–20 and 4–9% by 2100 under CSIRO and CNRM models, respectively. Intercropping short and medium duration pigeonpea varieties with maize will reduce pigeonpea yields by 60–80 and 70–90% under the CSIRO and CNRM model, respectively. There is a need to develop heat and waterlogging-tolerant pigeonpea varieties to help farmers adapt to climate change and to protect the huge pigeonpea export market currently enjoyed by Kenya.

Keywords: climate change impacts, semi-arid, adaptation, maize yields, pigeonpea varieties

1. Introduction

Kenya is the world's fourth largest producer of pigeonpea after India, Myanmar and Malawi, of which 99% is produced in semi-arid eastern Kenya, especially Machakos, Kitui, Makueni, Meru, Lower Embu, and Tharaka-Nithi Counties. It is also grown in the drier parts of Kirinyaga, Murang'a, and Kiambu Counties in Central Kenya; and some parts of Lamu, Kilifi, Kwale, Tana River, and Taita-Taveta Counties at the Coast; mainly by small-scale resource-poor farmers [1–6]. Most farmers intercrop pigeonpea with maize or sorghum on the same land, either in alternate or multiple rows, as a form of security against total crop failure [7].

Pigeonpea provides multiple benefits to the rural poor. Firstly, its protein-rich grain can be consumed both fresh and dry and provides a cheap source of protein for the poor farmers in the drylands. Secondly, its leaves and hulls are used as livestock feeds and the stem as fuelwood. Thirdly, it has the ability to enrich the soil through di-nitrogen fixation [8], litter fall and being a deep-rooted crop, to mobilize nutrients, particularly phosphorus, from the deep soil horizons [9–11]. Fourthly, intercropping pigeonpea with cereals enhances soil coverage, reduces soil erosion, and boosts cereal yields [9, 10]. Finally, the crop provides an assured source of income for farm families and foreign exchange for Kenya. About 7000 ton of dhal (dehulled pigeonpea) and 15,000 ton of whole grain are exported annually to Europe, North America, the Middle East, and India, but this figure represents just 30% of Kenya's export potential [1, 4–6, 12]. Thus, pigeonpea has immense untapped potential which if fully exploited could transform the lives of many communities and economies of many countries in the East African region. Maize on the other hand is the staple food for over 90% of Kenya's population and accounts for 56% of cultivated land in Kenya [13].

Despite the importance of maize-pigeonpea intercropping system in semi-arid Kenya and elsewhere in the region, their productivity has continued to decline. Maize and pigeonpea yields on farmers' fields are low, averaging 300–500 kg ha^{-1} against a yield potential of 2.5 t ha^{-1}, mainly due to non-use of improved varieties and poor farming practices, low soil fertility and climate variability [2, 6, 14]. The situation is bound to worsen in future with the expected change in climate. Temperatures and rainfall in Kenya and the rest of East Africa are expected to increase by about 2°C and 11%, respectively, by 2050 due to climate change [15–18]. However, the rise in temperature may cause a substantial increase in evaporation rates, which are likely to balance and exceed any benefit from the predicted increase in precipitation [19]. Thus, if not checked, climate change will undermine agricultural productivity and expose millions of people to hunger and poverty, especially in semi-arid areas where temperatures are already high and rainfall low and unreliable, agriculture is predominantly rain-fed and adoption of modern technologies is low [20, 21].

A lot of work has been done to quantify some of the agricultural impacts associated with projected changes in future climate using a variety of simulation models, but most of it has been carried out at global, regional and country levels hence not applicable to community-based adaptation planning [20, 22–24]. Similarly, despite the importance of pigeonpea in Kenya and elsewhere in the region, few studies have assessed the impact of climate change on its performance. Most studies have focused on staple and commercial crops such as maize, tea, wheat, rice, beans and groundnuts [20, 21, 25–27], and tomatoes [28]. There is a need for more detailed information on the impacts of climate change on pigeonpea-maize intercropping systems to guide in formulating appropriate adaptation measures that will increase their productivity, ensure food security in future, and safeguard pigeonpea's niche markets. Therefore, the objective of this study was to assess the impact of climate change under a range of scenarios on intercrops of maize and improved pigeonpea varieties developed and released in Kenya in recent times.

2. Materials and methods

2.1 Study area

The study was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) Katumani Research Centre in Machakos County, 80 km south-east of Nairobi (37°14′E and 1°35′S). Katumani has bimodal rainfall pattern and receives an average of 711 mm annually. The long rains (LR) occur from March to May and the short rains (SR) from October to December with peaks in April and November, respectively [7, 29]. Inter-seasonal rainfall variation is large with coefficient of variation ranging between 45 and 58% [30]. Temperatures range between 17 and 24°C with February and September being the hottest months. The mean annual temperature is 20°C. Evaporation rates are high and exceed the amount of rainfall, most of the year, except in the month of November. The mean potential evaporation is in the range of 1820–1840 mm per year whilst evapotranspiration is estimated at 1239 mm [31] giving an r/ETo ratio of 0.57. Katumani is 1600 m asl and the terrain ranges from flat to hilly with slopes varying from 2 to 20% [32]. It falls under agro-climatic zone IV which has a low potential for rain-fed agriculture [29]. The dominant soils are chromic Luvisols [33, 34], which are low in organic C, highly deficient in N and P and to some extent Zinc and generally have poor structure [35].

Mixed farming systems involving food crops and livestock are characteristic of the region. Crops grown are predominantly drought-escaping or early maturing varieties of pigeonpea, maize, beans, sorghum, and millet [29]. Due to the erratic nature of rainfall, most farmers around Katumani and the larger semi-arid Eastern Kenya prefer to intercrop maize with at least a legume (pigeonpea, beans, or cowpeas) on the same land. This is often done either in alternate or multiple rows and is seen by many farmers as a form of security against total crop failure [7]. Long duration pigeonpea is normally planted during SR in October–November and harvested in August–September the following year. Medium and short duration varieties can be planted and harvested in one season. Crop combinations, planting patterns, and plant populations of pigeonpea and other crops vary considerably, depending on the soil type, climate, and farmer's preferences. However, dominant pigeonpea cropping systems practiced in the region include: pigeonpea intercropped with maize, sorghum, millets, cowpea and green gram; pigeonpea and cowpea intercrops; and maize/bean/pigeonpea intercrops [1, 4–6].

2.2 Long-term simulation

Agricultural Production Systems Simulator (APSIM) version 7.3 was used to predict the impact of climate change on maize and pigeonpea yields in Katumani and similar areas in eastern Kenya. APSIM was preferred due to its user-friendliness, widespread application in the region and ability to make highly precise simulations/predictions once properly initialized [16, 36–40]. The APSIM has the capacity to predict the outcome of diverse range of farming systems and management practices under variable climatic conditions, both short and long term [39, 41–44]. It also simulates growth and yield of a range of crops in response to a variety of management practices, crop mixtures, and rotation sequences, including pastures and livestock [44]. The model runs with a daily time step and has four key components: (1) a set of biophysical modules that simulate biological and physical processes in farming systems, (2) a set of management modules that allow the user to specify the intended management rules that characterize the scenario being simulated and controls the conduct of the simulation, (3) various modules that facilitate data input and output to and from the simulation, and (4) a simulation engine that drives the simulation process and controls all messages passing between the independent modules [44, 45]. It has a user interface which allows selection of input data (climate, soil, crop, and management), output data from modules of interest (e.g., water balance, carbon, nitrogen and phosphorus balances, and crop growth and yield) management of simulation scenarios (saving, running, retrieving, and deleting), error checking (summary of scenario set-up inputs and run time operations), and output analysis via software links for viewing output data in text file, Excel, or graphs [44].

APSIM requires site-specific data on latitude and longitude, soil texture and depth (m), slope (%) and slope length (m); climate (daily maximum and minimum temperature [°C], daily solar radiation [MJ/m^2] and daily rainfall [mm]); crop growth and phenology (crop type and cultivar name, maturity type, date of 50% flowering and total number of leaves, total biomass at harvest (kg ha^{-1}), grain yield (kg ha^{-1}), final plant population (plts m^{-2}), N and P contents of plant parts, biomass at anthesis (kg ha^{-1}), population at thinning (plts m^{-2}), date of physiological maturity (black layer) and maximum leaf area index (LAI); soil water, nitrogen and phosphorus; residues and manure (crop and manure type, dry weight [kg ha^{-1}], N, C and P content [%], ash content, and ground cover [%]); and management (date of all operations e.g. sowing, harvest, thinning, weeding, tillage and fertilizer applications, sowing depth and plant population, type, rate and depth of fertilizer application, and type (hoe, disc, harrow, etc.) and depth of tillage) to run. These data can be obtained from field trials or secondary sources. However, this study used the APSIM that had been calibrated and validated for Katumani semi-arid area by Okwach and Simiyu [46] and Okwach [47].

Daily minimum and maximum temperature, solar radiation and rainfall data for Katumani for the near (2050) and far (2100) future scenarios were downscaled from the National Meteorological Research Centre (CNRM) and Commonwealth Scientific and Industrial Research Organization (CSIRO) climate models using the Statistical Downscaling Model (SDSM) version 4.2 [48] and uploaded in APSIM. Both models, CNRM and CSIRO, have predicted a 1–2.5°C and 10% increase in temperature and rainfall, respectively, by the end of the century (2100) which is consistent with the Intergovernmental Panel on Climate Change (IPCC)'s prediction of 3.2°C and 11% rise in temperature and rainfall, respectively, for Kenya and the rest of East Africa by 2100. SDSM is a decision support tool for assessing local climate change impacts using a robust statistical downscaling technique. It is a hybrid of a stochastic weather generator and regression-based downscaling methods and facilitates the rapid development of multiple, low-cost, single-site scenarios of daily surface weather variables under current and future climate [49]. The tool has been used extensively with remarkable success [49–55].

The following eight cropping systems were simulated using the downscaled climate data: (1) Sole short duration maize crop, (2) Sole short duration pigeonpea crop, (3) Sole medium duration pigeonpea crop, (4) Sole long duration pigeonpea crop, (5) Short duration pigeonpea-maize intercrop, (6) medium duration pigeonpea-maize intercrop and (8) long duration pigeonpea-maize intercrop. The model was run to simulate 50 and 100 years under these cropping systems. The growing season was defined to start after 5 consecutive days with volumetric soil water content in the top 100 cm above 70%. The end of the season was deemed to occur when soil water content fell below 50% for 8 consecutive days. KDVI maize variety was used to represent all early maturing (120–150 days to mature) and high yielding maize varieties recommended for semi-arid conditions. Similarly, Mbaazi I, Kat 60/8 and Mbaazi II pigeonpea varieties were used to represent short (100 days to mature), medium (150 days to mature) and long (180–220 days to mature) duration pigeonpea varieties, respectively. Pigeonpea was planted at spacings of 90 cm × 60 cm, 75 cm × 30 cm and 50 cm × 25 cm for the long, medium and short duration varieties, respectively, whilst maize was planted with Triple Super Phosphate (TSP) fertilizer at the recommended rate of 40 kg P_2O_5 ha^{-1} at spacing of 90 cm × 30 cm. Other agronomic practices were adopted as currently practiced by farmers such as early planting, timely weeding and thinning.

3. Results and discussion

3.1 Maize yields

Long-term yields of maize under variable and changing climate in Katumani are presented in **Figure 1**. Prospects for increased maize production under sole maize crop in Katumani (Machakos County) are high, both in the near (by 2050) and far (2100) future scenarios under the two climate models, CNRM and CSIRO models. Relative to baseline yield of 500 kg ha^{-1}, maize yields are expected to increase by 141 and 10% in 2050 and 2100, respectively, under the CSIRO model. The CNRM model was more optimistic and predicted maize yield increases of 150 and 23% in 2050 and 2100, respectively, under maize sole crop. The increase in yield could be attributed to the projected increase in rainfall of 20–40 mm per year by 2100. The predictions corroborate reports by Waithaka et al. [56] that Kenya's bread basket could shift from the Rift Valley to semi-arid eastern and north-eastern Kenya by 2050. Intercropping maize with pigeonpea will give mixed results. According to the CSIRO model, maize yield will increase by 18 and 15% under maize/Mbaazi I and maize/Mbaazi II intercrops, respectively, in 2050. However, yields under maize/Kat 60/8 intercrop will decline by 4% in the same period. A similar trend will be observed in 2100 where intercropping maize with pigeonpea will reduce maize yields by 10–20% under the CSIRO model. The projected decline in maize yield could be attributed to high evapotranspiration due to anticipated rise in temperature. According to Thornton et al. [18], high evapotranspiration is bound to cause water scarcity which will adversely affect maize growth. These results agree with Herrero *et al*. [20] who predicted maize yield losses of upto 50% in the ASALs due to climate change, albeit under the Hadley model. Thornton et al. [18], Jones and Thornton [25], and Downing [57] have also predicted a significant decline in yields of maize and other food crops in the East African region due to the same phenomenon. However, the decline in maize yield could be arrested by encouraging farmers to adopt irrigation, conservation agriculture, seed priming, and in-situ water harvesting among other adaptation measures [58].

Conversely, according to the CNRM model, intercropping will increase maize yields by 28 and 11% under maize/short duration pigeonpea and maize/medium

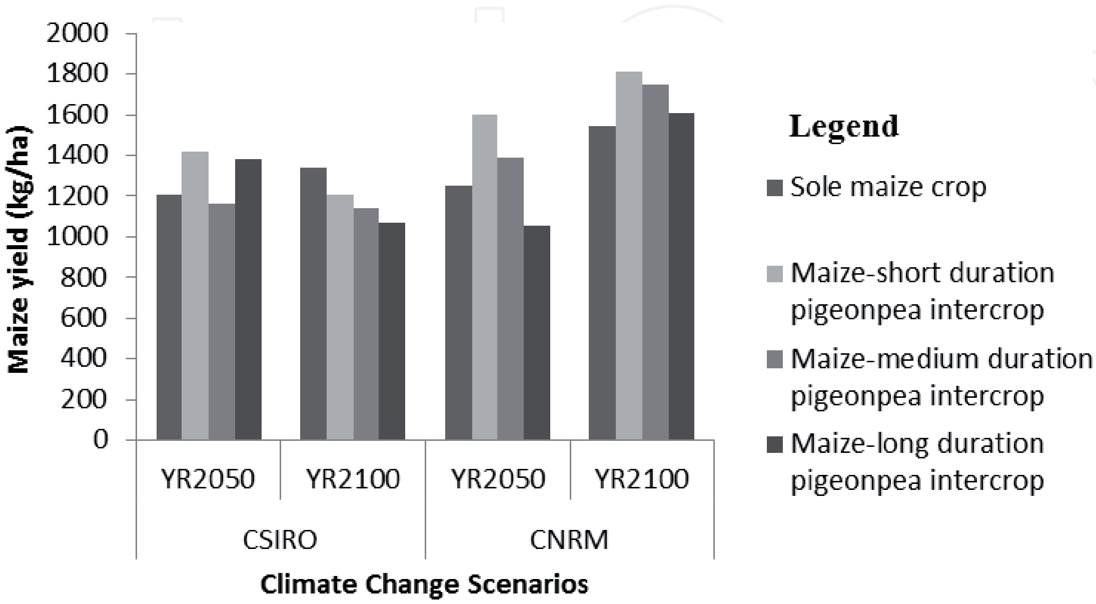

Figure 1.
Long-term effect of pigeonpea on maize yield in Katumani under variable and changing climate.

duration pigeonpea intercrops, respectively, by 2050. Maize yields under maize/long duration pigeonpea intercrop will declined by 16%. However, maize yields will increase by 18, 13, and 4% under maize/short duration pigeonpea, maize/medium duration pigeonpea and maize/long duration pigeonpea intercrops, respectively, in the far future (2100). Because of these conflicting results, it is difficult to generalize the impacts of climate change on maize yields from maize/pigeonpea intercrops in Katumani and similar areas in the country. Further simulations involving many GCM model X scenario combinations are therefore required to establish the correct direction of change in maize yields under these systems, whether they will increase or decrease. Meanwhile, the results corroborate observation by Herrero et al. [20] that climate change impacts on maize yields depend on the emission scenario, crop model and the Global Climate Change Model (GCM) used.

3.2 Pigeonpea yields

Long-term yields of pigeonpea under variable and changing climate in Katumani are presented in **Figure 2**. Unlike maize, both CSIRO and CNRM models predicted decreased pigeonpea yields in Katumani in the near and far future. Yields from sole pigeonpea crop will decline by 10–20% and 4–9% under CSIRO and CNRM models, respectively, by 2100. Intercropping short and medium duration pigeonpea varieties with maize will reduce pigeonpea yields by 60–80% and 70–90% under the CSIRO and CNRM model, respectively. However, long duration varieties will yield highest under the two Global Climate Change Models (GCMs) irrespective of the cropping system, but the yields will be much lower than the potential yield of over 2 t ha^{-1} obtained from research experiments and large-scale commercial farms in the region. The decline in pigeonpea yields could be attributed to the projected 2°C and 11% increase in temperature and rainfall, respectively. Pigeonpea is a Carbon-3 (C3) plant and is highly sensitive to waterlogging; therefore, existing pigeonpea varieties may not thrive in the predicted hotter and wetter conditions [59, 60]. High temperatures reduce the rate of photosynthesis in legumes due to their C3 photosynthesis cycle leading to low yields [61, 62]. Waterlogging blocks oxygen supply to roots which hamper permeability [63], delays flowering and reduces vegetative growth, photosynthetic rate, biomass and grain yield in pigeonpea [64, 65]. Short duration

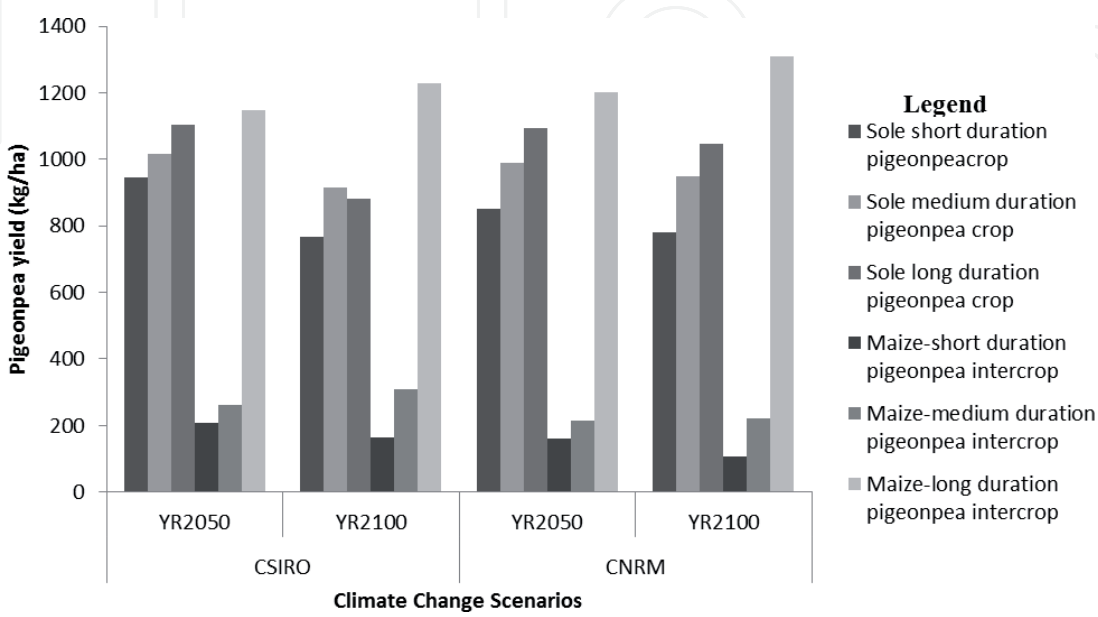

Figure 2.
Projected pigeonpea yields for Katumani in the near and far future.

pigeonpea varieties like Mbaazi I are more prone to the risk of yield reduction due to waterlogging compared to the medium and long duration varieties such as Kat 60/8 and Mbaazi II, respectively [66]. Therefore, farmers in Katumani and similar areas in the country may have to rethink their dependence on pigeonpea going into the future. Scientists also need to start breeding for more heat and waterlogging-tolerant varieties to save the livelihoods of thousands of resource-poor households in ASALs and safeguard the huge pigeonpea export market that Kenya currently commands.

4. Conclusion

Prospects for growing maize in Katumani are high both in the near (2050) and far (2100) future. However, pigeonpea production will be negatively affected by climate change going forward due to pigeonpea's susceptibility to high temperatures and waterlogging. Therefore, farmers in the ASALs need to rethink their dependence on pigeonpea while national plant breeding programs need to start developing heat and waterlogging-tolerant varieties to help thousands of resource-poor households in ASALs to adapt to climate change and protect the huge pigeonpea export market that Kenya currently enjoys.

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Author details

Kizito Musundi Kwena[1,2]*, G.N. Karuku[1], F.O. Ayuke[1] and A.O. Esilaba[3]

1 Department of Land Resource Management and Agricultural Technology (LARMAT), University of Nairobi, Nairobi, Kenya

2 Kenya Agricultural and Livestock Research Organization (KALRO), Katumani Research Centre, Machakos, Kenya

3 Kenya Agricultural and Livestock Research Organization (KALRO), Nairobi, Kenya

*Address all correspondence to: kwenakizito@yahoo.com

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