Tropical and Subtropical Agroecosystems

PREDICTING IMPACT OF CLIMATE CHANGE ON WATER REQUIREMENTS FOR DIRECTLY SOWN RAIN-FED SWEET POTATO IN THE SEMI-ARID KATUMANI REGION, KENYA †

[PREDECIENDO EL IMPACTO DEL CAMBIO CLIMÁTICO EN LAS NECESIDADES DE AGUA PARA LA PATATA DULCE DE SIEMBRA DIRECTA DURANTE EL PERIODO DE LLUVIA EN LA REGIÓN SEMIÁRIDA DE KATUMANI, KENIA]

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SUMMARY

Background: In the wake of the changing climate, the current water crisis has increasing relevance for the human race, hence estimation is an integral part of planning, development and management of water resources of the country based on several meteorological parameters. **Hypothesis.** No significant changes in water requirements sweet potato crop for the next 20 years in Katumani, Kenya. **Methodology:** The study predicted the implications of climate change on crop water requirements for the short rain seasons between 1991-2016 (baseline climate) and future from 2020-2039 (climate change) in Katumani with the aid of the CROPWAT 8.0 model. Crop Water Requirements (CWR) were projected in two scenarios: i) Average rainfall and temperature of baseline period (1991-2016), ii) rainfall and temperature predicted in 2039 based on Relative Concentration Pathways (RCP); 8.5 and 2.6 scenarios, adopting the global circulation models (GCM) of IPSL-CM5A-MR and GFDL-CM3 for predicting monthly rainfall and temperature, respectively. To achieve effective water allocation and planning, data on sweet potato water requirements, irrigation withdrawals, soil types and climate conditions were gathered from the study area. **Assumptions:** The study assumed no change in the conditions relating to irrigation and crop production in the future. **Results:** Sweet potato water requirement in the baseline period were modelled at 579.9mm whereas predicted under RCP 2.6 and 8.5 to be 634.1 and 639.3mm, respectively. Averagely, a 16.7% decrease in effective rainfall may increase the overall sweet potato WR by 10.2%. This may be due to increased temperature and reduced rainfall. **Implication:** Short rain season is the most appropriate for production of rain fed crops in Katumani. **Conclusion:** This study is useful in explaining the adverse impacts of climate change mostly on sweet potato water needs in Katumani and in helping to plan and manage water resources for many other crops in arid regions.
Key words: Water conservation; sweet potato production; irrigation scheduling; temperature and rainfall.

RESUMEN

Antecedentes: A raíz del cambio climático, la actual crisis del agua tiene mayor relevancia para la raza humana, por lo que la estimación es una parte integral de la planificación, el desarrollo y la gestión de los recursos hídricos del país con base en varios parámetros meteorológicos. **Hipótesis**. No existen cambios significativos en los requisitos de agua para el cultivo de camote durante los próximos 20 años en Katumani, Kenia. **Metodología:** El estudio predijo las implicaciones del cambio climático en los requisitos de agua de los cultivos para las temporadas de lluvia cortas entre 1991-2016 (clima de línea de base) y futuras de 2020-2039 (cambio climático) en Katumani con la ayuda del modelo CROPWAT 8.0. Las necesidades de agua de los cultivos (CWR) se proyectaron en dos escenarios: i) precipitación y temperatura promedio del período de referencia (1991-2016), ii) precipitación y temperatura pronosticadas en 2039 con base en las rutas de concentración relativa (RCP); Escenarios 8.5 y 2.6, adoptando los modelos de circulación global (GCM) de IPSL-CM5A-MR y GFDL-CM3 para predecir la precipitación y temperatura mensuales, respectivamente. Para lograr una asignación y planificación eficaz del agua, se recopilaron del área de estudio datos sobre las necesidades de agua de la batata, las extracciones de riego, los tipos de suelo y las condiciones climáticas. **Supuestos:** El estudio asumió que no habrá cambios en las condiciones relacionadas con el riego y la producción de cultivos en el futuro. **Resultados:** El requerimiento de agua de la batata en el período de la línea de base se modeló en 579,9 mm, mientras que el RCP 2.6 y 8.5 se predijo que serían 634.1 y 639.3 mm, respectivamente. En promedio, una disminución del 16,7% en la lluvia efectiva puede aumentar el WR total de la batata en un 10,2%. Esto puede deberse

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al aumento de la temperatura y la reducción de las precipitaciones. **Implicación:** La corta temporada de lluvias es la más apropiada para la producción de cultivos de secano en Katumani. **Conclusión:** Este estudio es útil para explicar los impactos adversos del cambio climático principalmente en las necesidades de agua de la batata en Katumani y para ayudar a planificar y administrar los recursos hídricos para muchos otros cultivos en regiones áridas.
Palabras clave: conservación de agua; producción de boniato; programación de riego; temperatura y lluvia.

INTRODUCTION

The advancement in agricultural modelling has smoothed precision farming and subsequently improved on producing crops (Muli *et al*., 2015). To adjust varying weather patterns, especially rainfall events, crop simulation models have compelled early warnings, thus aided in agricultural insurance (Johnson *et al*., 2018). Because of this, climate change has threatened food security, which has adversely affected smallholder farmers. (Niles and Salerno, 2018).

Globally, food security in the 21st century is threatened by climate change and projected to pose more significant impacts pertaining rain-fed agriculture (Mimi and Jamous, 2010). In most perspectives a shift in climate tends to lengthen growing seasons and rise in temperatures which may bring along negative implications such as reduced precipitation thus affecting availability of water and in turn crop water needs (Molua and Lambi, 2006; Eitzinger and Kubu, 2009).

The presence of crop water productivity models has paved way for the conjunctive assessment of environment and management factors that affect the attainment of optimal yields (Geerts *et al*., 2010). Combining crop water simulation models with a regular analysis of observed series of climate change scenarios, crop growth and measured soil water tension, could be optimized to resolve the varying weather conditions (Geerts *et al*., 2010). Crop simulation models mainly in-cooperate crop development, soil and meteorological data for the determination of crop water needs (Karuku *et al*., 2014).

Crop water requirements (CWR) have been predicted by various methods, however CROPWAT and AQUACROP models have been recommended by FAO since they are best suited at estimating CWR under various climate change scenarios (Raes *et al*., 2009). CROPWAT and AQUACROP are user-friendly models that have been widely used for computing crop water requirements and scheduling for supplemental irrigation of major rainfed crops (Oiganji *et al*.,2017). These computerized programs are convenient due to their simplistic to use and their input variables are much less strenuous compared to other models like DSSAT, ISAREG and APSIM (Karuku and Mbindah, 2020). CROPWAT is indeed a practical tool that allows scientists visualize results, make more informed decisions and achieve meaningful comparative output, and as such is suitable in the perspective of this study (Chowdhury *et al*., 2016). This model shows the percent reduction in yield resulting from water stress, and is therefore capable of calculating the requisite irrigation water needs to for optimal crop yields. (Muigai *et al*., 2019). A further exceptional feature of this model is that it is capable of extending deductions from studies to real scenarios that are yet to be tested in the field. (Allen *et al*., 1998). It also gives practical advice to farmers and extension agents on planning for additional irrigation and scheduling under varying water supply scenarios, for sustainable agriculture as well as crop growth conditions (Taylor and Bhasme, 2018).

In Kenya, several studies have predicted water consumption rates for various field crops in different regions. However, studies trying to focus on the potential impacts of climate change on CWR of sweet potato is lacking. Sweet potato is an important food crop since it provides dietary carbohydrates, vitamins and minerals as well as it is best fit in Eastern Kenya that is predominantly semi-arid (Kivuva, 2013). The study site experiences prolonged periods of drought thus reducing yield quality and quantity (Kivuva, 2013). In Katumani, sweet potato is mainly grown for food and its adoption has not been widely exploited probably due to variation in rainfall events that bring about problems in timing of planting dates (Mwololo *et al*., 2012). Farmers and agronomists strive to achieve sustainability in producing crops (Medrano *et al*., 2015). For a better managerial aspect of available scarce resources in crop production, it is more critical to understand CWR, the current level of water supplies and the possible implications of climate change in the future. The study aimed at understanding the implications of climate change on sweet potato water requirements in a semi-arid area and develop indicative irrigation schedules using the CROPWAT model as an early warning system to possible impacts of climate change and variation. Information obtained will be used in guiding farmers and agronomists on using available rainwater effectively as well as timing their crops' growth stages with rains and water requirements. These will promote the efficient effective use of such a limited resource and focus on improving realizable yields by farmers at local, county, national government and at global tiers.

MATERIALS AND METHODS

Study site description

The research was conducted at Katumani Research Centre in Machakos County, Kenya in the agro-ecological zone IV (Jaetzold *et al*. 2006) and at an altitude of 1624m asl; coordinates: latitudes -1.585543 and longitude 37.240090. The site experiences a bimodal rainfall distribution; with the long rains from March and to May and the short rains from November to mid-December. The average maximum and minimum temperature per day are 24.7 and 13.7 ^{o}C, respectively with a mean annual rainfall approximately 450-600 mm (Jaetzold *et al*., 2006). The average wind speed varies from 7-11kmhr^{-1}. The predominant soil types are Ferralo-Chromic Luvisols (USDA) of Makueni quartz -itic rock, having a sandy clay loam texture with a saturated hydraulic conductivity ranging from 0.91- 1.98 mhr^{-1} (Gicheru and Ita, 1987; Deckers *et al*., 2010; Mwendia *et al*., 2017). Total available water (TAW) ranges between 10-50 mm per meter of soil depth. The area is suitable for sweet potato (*Ipomoea batatas L.),* maize (*Zea mays)* Katumani variety, beans *(Phaseolus vulgaris)*, pigeon peas (*Cajanus cajan)* and mangoes *(Mangifera indica*).

Experimental design, layout and treatments

The experimental plots trials were established as a RCBD (Randomised Complete Block Design) with 3 blocks acting as replications and 5 treatments. A total of 15 experimental units of 4m by 5m long with a 0.5 m and 1m separating the plots and blocks, respectively. The vines were planted at a 0.25m by 0.6m spacing. Sweet potato was the main crop of interest with treatment combinations comprising of; sole Kabondo variety (orange-fleshed), sole Bungoma (white-fleshed variety, sole common beans *(mwezi mbili)*, Kabondo + common beans and Bungoma + common beans intercrop.

Agronomic practices on the experimental plots

Land was manually cleared with the aid of a hand hoe, whereas ridges constructed 1m apart. Planting was done at the onset of the rains and hand weeding done as soon as the weeds emerged. 200kg ha^{-1} NPK 15:15:15 was applied after land preparation through broadcasting prior to making the ridges for application of 30kg N + 30kg P_2O_5 + 30kg K_2O for all treatments. The beans were top-dressed 35 days after sowing with urea at the rate of 100kgha^{-1}. Pests and diseases were controlled upon incidence. Earthing up sweet potato ridges with soil was done as the need arose. Harvesting

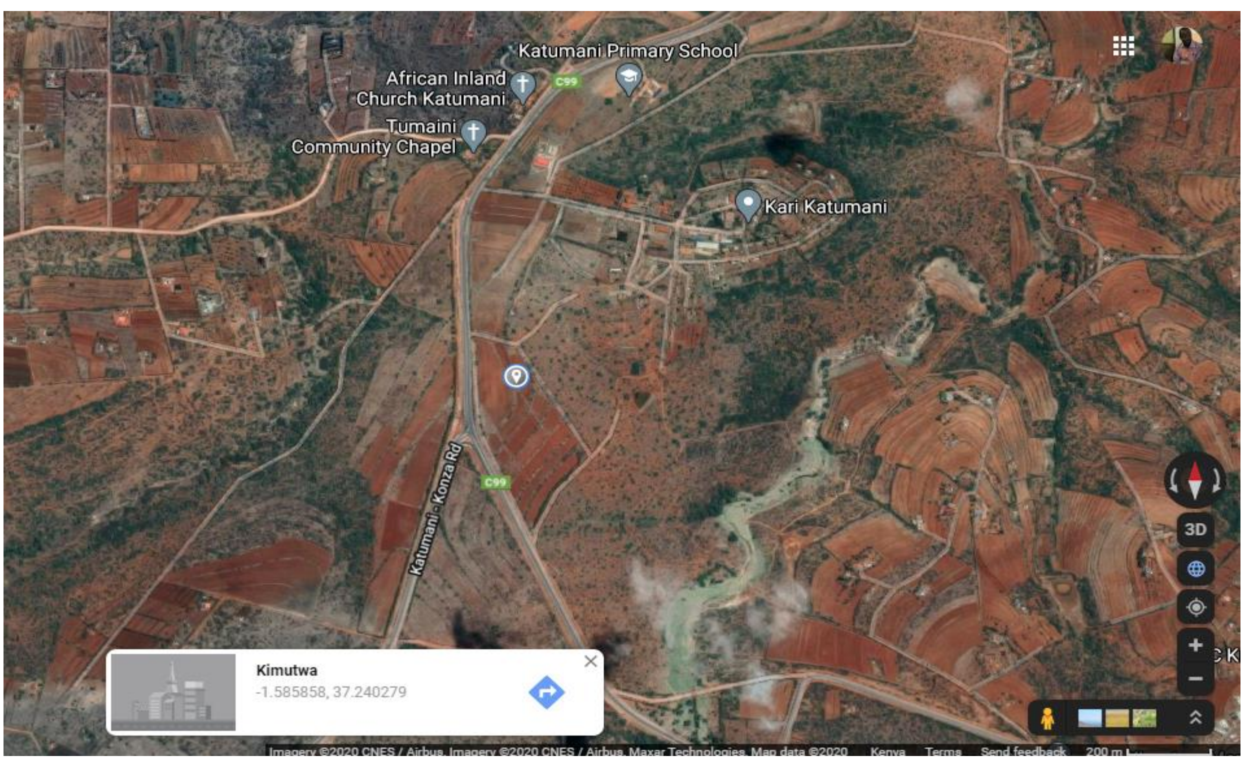

Figure 1. Location map of Katumani, Kenya; Source: Google Earth.

of sweet potato was done 160 days after planting (DAP) at the point when the end of the vines had started yellowing. This was made possible by hand digging with a hoe up the ridges and uprooting the entire plant and removing the tubers.

Climate model

The baseline and predicted weather elements Katumani were obtained from the Climate Change Knowledge Portal of the world bank (https://climateknowledgeportal.worldbank.org-2020). This was based on the Global Circulation Models (GCMs) adopting the IPSL-CM5A-MR and GFDL-CM3 since they provided a high correlation with the baseline average monthly precipitation and temperature, respectively (Scher, 2018; Nashwan and Shahid, 2020). This was achieved by keying in the study site's geographical coordinates. The GCM models projected; rainfall, maximum and minimum temperature based on four Representative Concentration Pathways (RCPs) representing the concentration of carbon delivering global warming per square meter across the earth. Such that; RCP 8.5 (High emission), a global warming of approximately 8.5 Wm^{-2}, with a decreasing magnitude to RCP 6.0, 4.5 and 2.6 Wm^{-2} (Wayne, 2014). Such magnitudes are projected to deliver a radiation temperature rise by 2100, relative to pre-industrial temperature (Masui *et al*., 2011). Higher RCP numbers describe a scarier fate: which implies that more carbon dioxide has been emitted to the atmosphere, hence warming the earth and acidifying the ocean. This implies RCP 2.6 and 8.5 as the best and worst-case scenarios, respectively. This study assumed that there was no change in the conditions relating to crop production in future as each year had one cropping season which was assumed to commence in October and tapper off in March.

Model description: CROPWAT

This is a computer-aided application for the calculation of crop water and irrigation needs based on; soil, climate and crop (Smith, 1992). It is an irrigation problem corresponding software which helps to determine the amount of water and timing of irrigation schedules under rain water supply based on monthly/ decade meteorological data obtained. A decade implies a 10-day-average derived as input for the calculations (Smith, 1992). Crop growth and soil data were collected directly from the field (Karuku *et al*., 2014; Ikudayisi and Adeyemo, 2017). The duration of the growth cycle was 160 days, the initiation period was 40 days, its vegetative growth was 42 days, the tuber was 39 days and the final stage was 39 days (Wohleb *et al*., 2014).

Crop water requirements (CWR)

In order to estimate water needs of sweet potato, the model required the following datasets from the site: (a) Monthly rainfall data (b) Sweet potato data included cropping pattern, dates of planting and harvesting, data on crop coefficients (K_c values), rooting depth and days at each growth stage, moisture depletion fraction (c) Total area planted (ha) (d) ET_o values based on daily/decade/monthly climatic data on relative humidity, sunshine hours, maximum and minimum temperature and the speed of wind, utilizing the Penman-Monteith (1948) equation as described by Beven (1979) and updated by Allen *et al*. (2006) in calculating crop evapotranspiration, Eqn 1.

$$\gamma ETo = \frac{\Delta(Rn - G) + \rho a\, Cp \frac{es - ea}{ra}}{\Delta + \gamma(1 + \frac{rs}{ra})} \quad (1)$$

Where Rn - net radiation, G- soil heat flux, (es - ea) - air vapour pressure deficit, ρa- mean air density under constant pressure, Cp- specific heat capacity of the air, Δ- slope of the relationship between saturation vapour pressure and temperature, γ is the psychometric constant, and rs and ra are the (bulk) surface and aerodynamic resistances.

Sweet potato water requirement was calculated using equation 2; (Gomes and Carr, 2003), based on the growth stage, crop coefficient values and the sites reference evapotranspiration and the results presented in Table 3, 4 and 5.

$$ET\ sweet\ potato = ETo \times Kc \quad (2)$$

Scheduling for irrigation

An irrigation schedule specifies the time and quantity of water to be supplied to the crop under soil moisture deficit conditions. It is primarily intended to supply water in the precise amounts and time. In order to accomplish these, the CROPWAT model required in-situ data on; (a) Name of soil, initial soil moisture depletion, maximum sweet potato rooting depth, total available moisture in soil (TAM) reflects the difference in moisture levels between field capacity and wilting point (b) Scheduling category had several computations relating to the timing as well as the depth of application which should be irrigated in order to restore the soils water status to field capacity once the available soil moisture has been exhausted.

Effective rainfall was computed based on the United States Department of Agriculture in the model, Soil Conservation Service (USDA-SCS) method as described by Dastane (1978) using Eqn 3.

$$eff = \frac{tot \times 125 - 0.2tot}{125} \qquad (3)$$

where, $_{eff}$ = effective rainfall (mm) and $_{tot}$ = total rainfall (mm) was used since $_{tot} \leq 250$ mm.

TAM was computed using FAO irrigation and drainage paper 56 Eqn 4.

$$TAM = 1000(\Theta\, fc - \Theta wp)Zr \qquad (4)$$

Where TAM-total available moisture in the root zone, FC-field capacity, WP-wilting point and Zr rooting depth of the crop in question.

Statistical analysis

This was done with the aid of GenStat 19th edition (Lane and Payne, 1997). A two-way ANOVA was used to determine means significant differences in the baseline (1991-2016) and projected (2020-2039) sweet potato water needs. A Bonferroni test of significance was performed at $P \leq 0.05$ on climate change scenarios effect on sweet potato irrigation and water use.

RESULTS AND DISCUSSION

Weather data

The modeled baseline and predicted monthly climatic data are shown in Table 1 and 2, respectively.

Reference evapotranspiration

Reference evapotranspiration (ET_o) values in the baseline period (1991-2016) and predicted scenarios are presented in Table 1 and 2, respectively. In the baseline period, ETo values ranged from 33–49 $m^{-3}ha^{-1}day^{-1}$. The highest ETo values observed in march and February were 49.3 and 49.4$m^{-3}ha^{-1}day^{-1}$, respectively. On the other hand, the lowest ETo recorded in June and July were 34.5 and33.6 $m^{-3}ha^{-1}day^{-1}$, respectively. ETo reflects the capacity of atmospheric evaporation on the crop water needs relative to the prevailing weather conditions (Croitoru *et al.*, 2013). The higher ETo could be due to the low amount of rainfall received in February and march as well as high temperatures experienced which depicted dry summer conditions. Such variations in ET_o may be an indicator of how the time of planting tends to affect the crop water needs and the resultant economic yield. Essentially, CWR are mainly pegged on the balance between rainfall and evapotranspiration (root and leaf demand), thus influencing soil moisture status which may call for supplemental irrigation (Doria, 2011). In 2020-2039, the projected ETo ranged between 39 to 57 $m^{-3}ha^{-1}day^{-1}$ for both RCP 2.6 and 8.5. Similar to the baseline period, highest projected ETo were 56.8 and 5.69 $m^{-3}ha^{-1}day^{-1}$ for RCP 2.6 and 8.5, in February and march, respectively. On the other hand, the lowest projected ETo in RCP 2.6 and 8.5 was and 38.7 and 38.9 $m^{-3}ha^{-1}day^{-1}$, respectively. 2020-2039 was projected to experience 13.5 % rise in mean annual ETo. Additionally, a rise in the projected ETo may generate

Table 1. Monthly climatic data experienced during the baseline period 1991-2016.

Month	T-Min°C	T-Max°C	RH %	Wind (km/day)	SH	Rad (MJ/m²/day	ETo (mm/day)	Rain (mm)	Eff rain (mm)
January	12.3	25.5	69	95	10.5	25.2	4.53	32.9	31.2
February	13.2	26.4	59	112	10.4	25.7	4.93	23.6	22.7
March	12.4	26.7	49	120	9.3	24.1	4.94	58.9	53.3
April	11.7	26.1	60	112	7.9	21.1	4.25	113	92.6
May	11.4	25.2	68	95	7.7	19.6	3.72	82.3	71.5
June	10.7	24.1	70	95	7.7	18.8	3.45	35.9	33.8
July	10.2	23.5	61	112	6	16.7	3.36	26.6	25.5
August	10.4	23.8	52	130	4.9	16.1	3.62	30.8	29.3
September	11.2	24.6	61	166	7.5	20.9	4.31	28.8	27.5
October	11.8	25.3	69	164	8.6	22.8	4.46	66.6	59.5
November	11.6	25.1	73	120	8.1	21.6	4.07	102.4	85.6
December	11.2	25.1	79	112	8.6	22	3.97	55.9	50.9
Mean	11.5	25.1	64	119	8.1	21.2	4.14	657.7	583.3

Key: RH; relative humidity, T-max; maximum temperature, T-min; minimum temperature, SH; sun hours per day, Rad; radiation; ETo; evapotranspiration; Source: https://climateknowledgeportal.worldbank.org

Table 2. Predicted monthly climate for the year 2039.

	RCP 2.6 (2039)					RCP 8.5 (2039)				
Month	T-Min°C	T-Max°C	Rain (mm)	ER (mm)	ETo (mm/day)	T-Min°C	T-Max°C	Rain (mm)	ETo (mm/day)	ER (mm)
Jan	18.8	29.3	21	20.3	5.01	18.6	29.6	23.9	4.99	23
Feb	19.6	32.1	22.3	21.5	5.58	20	32.3	18.8	5.61	18.2
Mar	21	33.2	49.6	45.7	5.68	21	33.3	49.4	5.69	45.5
Apr	22.1	32.6	110.3	33.2	5	22.1	32.9	41.9	5.03	88.2
May	21.8	30.5	87.9	43.2	4.36	21.8	30.7	43.6	4.38	71.6
Jun	20.3	28.8	28.1	26.8	4	20.3	29.1	31.6	4.01	30
Jul	19.6	28.7	25.8	24.7	3.87	19.9	28.9	25.5	3.89	24.5
Aug	20	28.9	29.9	28.5	4.16	20.1	29.3	27.8	4.19	26.6
Sep	20.6	29.6	27.5	26.3	4.99	20.7	29.7	24.1	5.01	23.2
Oct	20.8	28.6	35.2	90.8	5.05	20.9	28.4	106.2	5.03	39.1
Nov	20.1	26.1	55.4	50.5	4.42	20.2	26.3	56.3	4.46	51.2
Dec	18.9	26.2	45.5	75.5	4.26	18.8	23.6	82.5	4.08	40.6
Mean	20.3	29.6	538.5	486.1	4.7	20.4	29.5	531.6	4.7	481.6

Key: T-max; maximum temperature, T-min; minimum temperature, ETo; evapotranspiration, ER; Effective rainfall; Source: https://climateknowledgeportal.worldbank.org

stress to sweet potato as a result of intense evapotranspiration experienced thus, affecting its water requirements as well as modifying its growth cycle (Motsa *et al*., 2015. Such may be due to the decreasing humid conditions predicted thus, a premonition that the highest sweet CWU may be experienced in 2039, especially in February and March whereas lowest in June and July. Therefore, most crops under rainfed should be grown between October and March in Katumani since projections indicate that most crop will have a low water consumptive rate (Table 3 and 4).

Effective rainfall

Rainfall is pivotal when it comes to rainfed agriculture like Katumani. Its distribution and intensity effects the production of crops, since agricultural drought turns out to be the major uncertainty in attaining food security. Effective rainfall of Katumani was computed based on the (USDA Soil Conservation Service) from rainfall received during the baseline period and that projected to occur between 2020-2039. The total effective rainfall received in in the baseline period was 583.3mm, with lowest recorded in February, July and September being 22.7mm, 25.5mm and 27.5mm, respectively. This preceded the start of the second short rain season. This short rain season recorded a higher effective rainfall in October, November and December having 66.6mm, 102.4mm and 55.9 mm, respectively. However, this was not the same case in January and February which recorded a low amount of rainfall; 32.9mm and 23.6mm, respectively. On the other hand, the predicted annual effective rainfall from 2020-2039 was 486.1 and 481.6mm from RCP 2.6 and 8.5, respectively; recorded a 16.7% decline. Discrepancies in the proportion of effective rainfall received during the baseline and projected period may be due to climate change and variation and showed that the effect of rainfall variations may lead to an increase in irrigation water needs. In this regard, planting sweet potato between low rainfall months from June to September under rainfed conditions may bring about discrepancies in available water as the crop may demand a higher amount of irrigation water to argument for its transpiration needs to satisfy the atmospheric evaporative demand (Karuku *et al*., 2014), thus suitable under irrigated conditions. Under such conditions of limited rain water availability, farmers may choose to irrigate or shift the cropping patters as they are assumed to strongly influence irrigation water needs (Döll, 2002).

Temperature

Temperatures observed during the baseline cropping season ranged from 10°C to 26°C with the highest recorded in March and lowest in July as 26.7 and 10.2 °C, respectively. However, this temperature range has been considered high for sweet potato production by Negeve *et al*. (1992), which thrives well at 15-25 °C. On the other hand, the projected mean annual temperature from 2020-2039 will be 6.7°C higher than one experience during the baseline period (1991-2016). As such, average maximum and minimum temperature were 29.6 and 20.3°C, and 29.5 and 20.4°C for RCP 2.6 and 8.5, respectively. This was a 36.3% increase in mean annual temperatures, thereby suggesting a significant warming trend in the study area. Chowdhury *et al*. (2013) had similar findings and stated that a 1% increase in temperature may increase the overall CWR by 2.9% and concurs with our study.

For sweet potato production, temperatures < 15°C deter root formation, whereas those >25°C affect photosynthesis as well as partitioning of biomass since the plants to use more energy for respiration for their maintenance and with less to support their growth (Eguchi *et al*., 2003). Additionally, higher temperatures cause plants to complete their growth cycle more rapidly with less time to reproduce and more likely, lower sweet potato yields (Craufurd and Wheeler, 2009; Hatfield *et al*., 2011). The shorter life span in sweet potato may be probably due to variances in partitioning dry mater to fibrous roots rather than the storage roots thus reducing the sink strength of the test crop (Thorne *et al*., 1983).

Crop and irrigation water requirement (CWR and CIR)

Effects of climate change on sweet potato water needs

Tables 3, 4 and 5 indicates the baseline and predicted modelled WR for sweet potato.

The modelled baseline period sweet potato water requirements for the short rain season were 597.9mm, whereas the predicted were 631.4 and 639.3mm, based on RCP 2.6 and 8.5 scenarios, respectively. From the observed baseline period, the highest ET sweet potato was at the tuber bulking stage (mid-season) amounting to 56.5mmdec^{-1}, with lowest recorded during initiation 14.8 mmdec^{-1}. During the sweet potato tuber bulking stage, the ET increased from 5.12, 5.47, 6.63 and 5.8 mmday^{-1} for decade 1, 2 3 and 1, respectively (Table 3). Similarly, the total effective rainfall in these stages was 38.5 and 89.5 mmdec^{-1} at the sweet potato tuber bulking and initiation stages, respectively. The low kc value recorded at sweet potato initiation stage (0.4) signified that the crop had not been fully developed and hence water losses were mainly through evaporation from the soil hence low water needs. Similarly, the high kc value at tuber bulking stage (1.19) showed a fully developed sweet potato crop, with a larger leaf area and canopy cover and thereby having a high-water use and hence it needed much water for to argument for the one transpires (Karuku *et al*., 2014). This is because the sweet potato had increased its proportion of transpiration relative to the amount of soil evaporation. Sweet potato sensitivity to water shortages sets in at the tuber bulking stage and therefore effective rainfall recorded at the bulking stage was not sufficient for the production of biomass which probably may have led to the entire sweet potato yield reduction (Ky) (Gajanayake *et al*., 2013).

Table 3. Sweet potato water requirement for under rain fed agriculture in Katumani Research station for the baseline period (1991-2016).

Month	Decade	Stage	Kc coeff	ETc (mm/day)	ETc (mm/dec)	Eff rain(mm/dec)	CIR (mm/dec)
Oct	2	Init	0.4	1.78	7.1	8	0
Oct	3	Init	0.4	1.73	19	22.9	0
Nov	1	Init	0.4	1.68	16.8	27.5	0
Nov	2	Init	0.4	1.63	16.3	31.4	0
Nov	3	Deve	0.43	1.73	17.3	26.6	0
Dec	1	Deve	0.6	2.41	24.1	20.4	3.7
Dec	2	Deve	0.79	3.16	31.6	16.3	15.3
Dec	3	Deve	1	4.14	45.6	14.3	31.2
Jan	1	Mid	1.18	5.12	51.2	12.2	39
Jan	2	Mid	1.21	5.47	54.7	9.9	44.8
Jan	3	Mid	1.21	5.63	62	9.1	52.8
Feb	1	Mid	1.21	5.8	58	7.3	50.7
Feb	2	Late	1.16	5.75	57.5	5.8	51.7
Feb	3	Late	0.99	4.89	39.1	9.8	29.3
Mar	1	Late	0.8	3.97	39.7	14.1	25.6
Mar	2	Late	0.6	2.95	29.5	17.4	12.1
Mar	3	Late	0.44	2.08	10.4	10	0
Cumulative					579.9	263.1	356.1

Key: Init; initiation; Dev = development, Mid; reproductive, late; maturity, Eff; effective rain, CIR; Crop irrigation requirements, Kc; crop coefficient, ETc: sweet potato crop evapotranspiration.

Table 4. Predicted water requirement for sweet potato under rain fed agriculture in Katumani Research station in 2039 based on RCP 2.6.

Month	Decade	Stage	Kc coeff	ETc (mm/day)	ETc (mm/dec)	Eff rain (mm/dec)	CIR (mm)
Oct	2	Init	0.4	0.81	8.1	4.2	2.8
Oct	3	Init	0.4	2.13	21.3	12.7	8.6
Nov	1	Init	0.4	1.85	18.5	15.7	2.8
Nov	2	Init	0.4	1.77	17.7	18	0
Nov	3	Deve	0.43	1.87	18.7	16.7	2
Dec	1	Deve	0.6	2.53	25.3	15.4	9.9
Dec	2	Deve	0.78	3.26	32.6	14.7	17.9
Dec	3	Deve	0.98	4.35	47.9	12	35.8
Jan	1	Mid	1.16	5.51	55.1	8.5	46.6
Jan	2	Mid	1.19	5.94	59.4	5.7	53.7
Jan	3	Mid	1.19	6.17	67.8	6.2	61.6
Feb	1	Mid	1.19	6.39	63.9	6.3	57.6
Feb	2	Late	1.14	6.38	63.8	6.1	57.6
Feb	3	Late	0.97	5.47	43.7	9.2	34.6
Mar	1	Late	0.79	4.47	44.7	11.9	32.8
Mar	2	Late	0.59	3.36	33.6	14.3	19.3
Mar	3	Late	0.44	2.4	12	8.9	2.2
Cumulative					634.1	186.6	445.9

Key: Init; initiation; Dev = development, Mid; reproductive, late; maturity, Eff; effective rain, CIR; Crop irrigation requirements, Kc; crop coefficient, ETc; sweet potato crop evapotranspiration.

Table 5. Predicted crop water requirement for sweet potato under rain fed agriculture in Katumani Research station in 2039 based on RCP 8.5.

Month	Decade	Stage	Kc coeff	ETc (mm/day)	ETc (mm/dec)	Eff rain (mm/dec)	CIR (mm).
Oct	2	Init	0.4	0.81	8.1	5.3	1.5
Oct	3	Init	0.4	1.93	21.3	14.5	6.8
Nov	1	Init	0.4	1.85	18.5	16.4	2.1
Nov	2	Init	0.4	1.77	17.7	18.1	0
Nov	3	Deve	0.43	1.88	18.8	16.6	2.2
Dec	1	Deve	0.6	2.59	25.9	14.9	11
Dec	2	Deve	0.78	3.36	33.6	13.8	19.8
Dec	3	Deve	0.98	4.45	48.9	11.8	37.2
Jan	1	Mid	1.16	5.54	55.4	9.2	46.2
Jan	2	Mid	1.19	5.97	59.7	7.1	52.6
Jan	3	Mid	1.19	6.2	68.2	6.8	61.4
Feb	1	Mid	1.19	6.43	64.3	5.6	58.7
Feb	2	Late	1.15	6.42	64.2	4.6	59.7
Feb	3	Late	0.98	5.5	44	8.1	35.9
Mar	1	Late	0.79	4.5	45	11.7	33.3
Mar	2	Late	0.59	3.37	33.7	14.5	19.2
Mar	3	Late	0.44	2.41	24.1	8.8	2.3
Cumulative					639.3	187.8	449.7

Key: Init; initiation; Dev = development, Mid; reproductive, late; maturity, Eff; effective rain, CIR; Crop irrigation requirements, Kc; crop coefficient, ETc; sweet potato crop evapotranspiration.

The projected modeled sweet potato water requirements between 2020-2039 were significantly ($p<0.05$) higher than the baseline period, demonstrating implication of climate change on the soil water balance, and hence resulting to changes of soil evaporation and plant transpiration and thus impacting on water productivity. Increasing CWR may pose a major challenge to the non-renewable ground water resources in Katumani region. Such observations concur with the highest amount of predicted sweet potato irrigation water needs in Table 4 and 5. Similarly, Onyancha *et al.* (2017) within the same

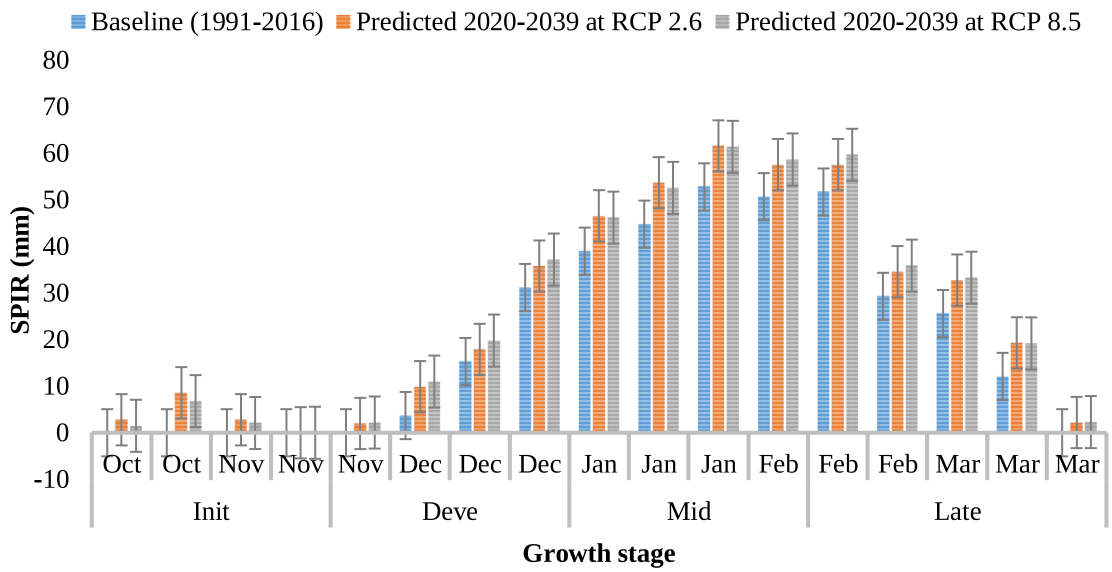

Figure 3. Trends in sweet potato irrigation requirements for the short rain season of baseline period (1991-2016) and predicted from 2020-2039. Error bars presents standard errors of mean irrigation demands.

county in Mwala, recorded 674.9mm water needs for maize during the dry season, stating that most crops parade a higher water use during dry season compared to the wet ones. In regions characterized with warm-dry seasons have a maximum water use (ETc), then the warm-wet season have a low water use, similar to our case. The modeled projected ET sweet potato at RCP 2.6 during; initiation, vegetative, tuber bulking and at harvest were 65.6, 124.2, 246.2 and 197.8 mm, respectively. This calls for a higher irrigation water demand to meet sweet potato evapotranspiration demand in Table 4 and 5. At the tuber bulking stage, the actual evapotranspiration is projected to be less than the maximum crop evapotranspiration (ETa<ETm) and therefore the crop is expected to experience water deficits and the model suggested an irrigation requirement of 219.5 mm in order to realize optimal yields. This clearly shows that future predictions of climate change especially in areas with high rainfall will receive more while the dry areas will become drier and thus have a higher demand for water (Liu and Allan, 2013). This reduction in rainfall will have a greater impact in areas where soils have a low level of organic carbon and therefore retain less water at low moisture potential, thus calling for appropriate soil and water management strategies (Clair and Lynch, 2010).

Climate change effects on sweet potato irrigation requirements (SPIR)

Trends in sweet potato irrigation water needs across all growth stages are presented in Figure 3.

Table 6. Effects of climate change on predicted mean sweet potato irrigation needs.

	1991-2016	2020-2039	
Growth stage	Baseline	RCP 2.6	RCP 8.5
Initiation	0.00[a]	3.55[a]	2.6[a]
Development	12.55[ab]	16.40[a]	17.55[a]
Tuber bulking	29.68[bc]	54.88[b]	54.73[b]
Harvest	46.83[c]	29.30[ab]	30.08[ab]
F pr.	<.001	0.001	0.001

The different letters within the same row shows significant differences between the comparing variables at $p < 0.05$.

SPIR is the amount of additional water needed for irrigation beyond precipitation in order to meet the growing season requirements for water to ensure optimum yield (Keller *et al*., 2008). Depicts differences between ETm and Effective Rainfall (ER) (Eteng and Nwagbara, 2014). SPIR for the baseline scenario were modeled at 356.1 mm, significantly lower than ($P<0.05$) the predicted were at 445.8 and 449.9 mm at RCP 2.6 and 8.5, respectively; recording a 26.3% increase which may be alluded to a climate-dependent shift that decreased precipitation, in line with the findings of (Döll, 2002). In C3 plants like sweet potato, photosynthesis relies mainly on CO_2 concentration (Flexas and Medrano, 2002). When crop water needs are not met, water deficit may lead to stomatal closure thus reducing the amount of water lost through evapotranspiration (Blum, 2009). Though, when the soil and plant water status are not replenished, stomatal closure lessens CO_2 uptake hence reduction in biomass production. In the presence of global warming, an increase in ET and CO_2 will lead to decrease in soil moisture deterring the soil- plant water relations (Kimball and Bernacchi, 2006). Similarly, the proportion of water transpired per unit CO_2 fixed brings about a crops transpiration efficiency (TE) (Blum,2011). Under drought like conditions, TE plays a vital role in maximizing the production of biomass and the crops' primary productivity through increased CO_2 fixation (Gherardi, and Sala, 2020). This accounts for the high irrigation requirements at the tuber bulking stage (mid) in all modeled scenarios. Such that; deficits in sweet potato water needs may lead to reduced growth and development hence yields may be affected (Kassam and Smith, 2001). Different ASALs poise varied behavior with response to the variation of rainfall and temperatures thus, farmers and agronomist should embrace irrigation schedules. Proper scheduling of irrigation will increase sweet potato yield, thus conserving water and energy, thereby reducing environmental impacts.

Developing indicative irrigation schedules for rain-fed sweet potato

Modeled baseline and projected irrigation schedules for sweet potato are present in Table 7.

Table 7. Actual irrigation requirement, deficiency irrigation and moisture deficit at harvest of rain-fed sweet potato.

Parameter	Sweet potato		
	(1991-2016)	Predicted (2020-2039)	
	Base-line	RCP 2.8	RCP 8.5
Total rainfall loss (mm)	134.7	47.7	67.3
Total irrigation losses (mm)	nil	nil	nil
ETa (mm)	577.8	631.3	636.7
ETm (mm)	577.8	631.7	636.9
Yield response Ky	0.9	0.9	0.9
Deficiency irrigation schedule (%)	nil	0.1	0.0
Efficiency irrigation schedule (%)	100%	100	100
Moisture deficit at harvest (mm)	7.6	26.0	4.8
Actual irrigation requirement(mm)	452.3	477.4	500.4
Efficiency in rainfall (%)	54.9	76.4	67.0

The crop evapotranspiration (ETa) required in attaining optimal sweet potato yields in Katumani during the baseline period with the aid of CROPWAT model was 579.9 mm (Table 3). Additionally, actual evapotranspiration (ETa) was equal to maximum evapotranspiration (ETm) at 577.8 mm for baseline. As such, maximum evapotranspiration (ETm) depicts growth conditions when soil water supply is not limited (Allen *et al*., 1998). Therefore, the modelled baseline available soil water was adequate to the crop for 160 days as the soil supplies water adequate hence the crops evapotranspiration demand and water uptake were equal, hence nil deficiency irrigation schedule recorded. However, upon maturity sweet potato encountered a 7.6 mm moisture deficit at harvest, water lost to runoff may increase deficits during rainy seasons and thereby requiring 452.3 mm irrigation water.

The predicted CWR from 2020-2039 based on GCM at RCP 2.6 and 8.5 were 634.1 and 639.3mm, respectively. Similarly, ETa and ETm using the RCP 2.6 scenario were 631.3 and 631.7mm, respectively whereas at RCP 8.5 were 636.7 and 636.9 mm, respectively. Under the modeled scenarios, ETa ≤ ETm, which implied that water supply was limited, hence sweet potato water requirements were not fully met, resulting to 0.1% yield reduction, that is reflected in the overall economic yield, hence a 477.4 and 500.4mm supplemental irrigation is required for optimal yields under RCP 2.6 and 8.5, respectively. A 0.9 Yield response (Ky) was also predicted to occur under both GCMs. Ky showed the relationship between production and water use sweet potato crop. The modelled Ky <1, showed that sweet potato was tolerant to water deficits and hence experienced a lesser reduction in yield with low water use. Sweet potato Ky <1 acted as a synthesis parameter in measuring its tolerance to water stress and an indicator to promoting successful irrigation schedules (Doorenbos and Kassam, 1979).

The baseline scenario experience nil reduction in ETc upon sweet potato maturity and in all other growth stages. This probably happened because Eta was equal to ETm implying that sweet potato fully transpired and hence met its atmospheric evaporative demand since there was sufficient moisture supply in the growth stages. Similarly, the predicted reduction in ETc in 2039 based in RCP 2.6 and 8.5 were 0.1 and nil at maturity and were considered negligible. However, at initiation, a 0.6 and 0.3% reduction in ETc was also projected to occur by RCP 2.6 and 8.5, respectively. This could be due to the rising atmospheric CO_2, increased saturation vapor pressure deficit and low soil moisture content caused by changes in precipitation thus affecting the soil water balance, resulting to ETa ≤ ETm (Kruijt *et al*., 2008). This shows that in the

Table 8. Crop yield and evapotranspiration reductions at each phenological development stage.

Time	Scenarios	Growth stage	Ini	Dev	Rep	Mt	Season
1991-2016	baseline	Reduction in ETc	0	0	0	0	0%
		Yield response factor Ky	0.2	0.4	0.55	0.2	0.9
		Yield Reduction	0	0	0	0	
		Cumulative yield reduction	0	0	0	0	0%
Predicted 2020-2039	RCP 2.6	Reduction in ETc	0.6	0	0	0	0.1%
		Yield response factor Ky	0.2	0.4	0.55	0.2	0.9
		Yield Reduction	0.1	0	0	0	
		Cumulative yield reduction	0.1	0.1	0.1	0.1	0.1%
	RCP 8.5	Reduction in ETc	0.3	0	0	0	0%
		Yield response factor Ky	0.2	0.4	0.55	0.2	0.9
		Yield Reduction	0.1	0	0	0	
		Cumulative yield reduction	0.1	0.1	0.1	0.1	0%

Key: ETc; crop evapotranspiration and Ky; yield reduction factor, Ini; initiation (40days), Dev: development (42 days), Rep; reproductive (39days), Mat: maturity (39 days).

phase of climate change the crop was resilient and hence minimal loss of yield is expected.

CONCLUSION

Climate change in 2039 based on GCM on RCP 2.6 and 8.5 will affect the production of sweet potatoes in the study area as follows;

- Average annual temperatures will rise by 36.3% hence shorten the sweet potato growth period by 42 day thus lowering the optimal yields.
- Annual effective rainfall will be reduced by 16.7% thus modifying evaporation, runoff and soil moisture storage leading to an increased demand for irrigation water.
- Sweet potato water requirements will increase by 10.2% hence a decline in yields is expected.
- Supplemental irrigation will increase by 26.3% as an impact of climate change.
- Farmers are required to brace themselves with appropriate water conservation practices to increase their resilience in future when climate change impact is felt particularly in the ASALs of Kenya.

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