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Climate change scenario projections and their implications on food systems in Taita Taveta County, Kenya

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Abstract

This study explored how Taita Taveta County could use the power of climate scenarios in planning agricultural activities on food systems to enhance sustainable food. The study involved the use of climate scenarios to model the past, present and future climate with the view of predicting probable changes in climate and how these changes may impact on food production, transformation and utilization and the ultimate handling of ensuing food wastes to mitigate the looming climate change scenarios. The research was conducted in Taita Taveta County that is characterized into three agro-ecological zones based on altitude and an ensemble of the top two models (ICHEC-EC-EARTH and MPI-M-MPI-ESM-LR) was used to analyse climate projections following RCP4.5 and RCP8.5 pathways. Rainfall and temperature from the Kenya Meteorological Department and supplemented with datasets from Kenya Agricultural and Livestock Research Organization (KALRO), Climate Hazard Group Infrared Precipitation with Stations (CHIRPS) and European Centre for Medium-Range Weather Forecast Reanalysis v5 (ERA5) respectively for the period 1981–2021 were used. The results exhibited occurrences of climate variability and change, and the seasons when the rainfall amounts were highest and lowest. Projected temperatures up to 2065 revealed likelihood of significant future warming and predicted future rainfall variations indicated insignificant increase. The study concluded by predicting a significant rise in temperatures and insignificant increase in rainfall leading to probable decrease in food production. The study recommended adoption climate smart technologies and early warning systems by the communities and policy makers to mainstream climate information in food systems, particularly production, transformation and utilization to enhance efficiency and avoid unnecessary wastage. State and non-state actors and other stakeholders could leverage these results to devise suitable adaptation and mitigation measures in the county.

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Data Availability Statement: There are no notable legal or ethical issues. In the introduction of the interview schedules, I undertook to keep the data sources anonymous by not disclosing the identity of respondents. Sources of data are acknowledged in the manuscript. Prior to embarking on field data collection, an introductory letter was issued to the lead researcher giving approval for the study. The researcher sought permission and a research permit was issued by the National Council for Science, Technology and Innovation (NACOSTI). A copy of the final report of the study will be shared with NACOSTI as a National repository for research where the findings are publicly available to the public either physically or electronically on the organization's website. I also confirm that all relevant data has been included as Supporting Information files.

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1. Introduction

A food system (FS) encompasses the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption and disposal of food products that originate from agriculture, forestry or fisheries. The FS is comprised of sub-systems such as farming system, waste management system, input supply system. A sustainable food system (SFS) is a food system that delivers food security and nutrition for all in economic, social and environmental bases without compromising the ability of future generations [1]. A SFS provides healthy food to people and creates a balanced environmental, economic and social systems surrounding the food. SFS starts with the development of sustainable agricultural practices, food distribution systems, creation of sustainable diets and reduction of wastes throughout the system.

International Food Policy Research Institute (IFPRI) defines Food systems as the sum of actors and interactions along the food value chain—from input supply and production of crops, livestock, fish, and other agricultural commodities to transportation, processing, retailing, wholesaling, and preparation of foods to consumption and disposal of wastes from food processes [2]. Food systems also include the enabling policy environments and cultural norms around food. Ideal food systems would be nutrition-, health-, and safety-driven, productive and efficient, environmentally sustainable, climate-smart, and inclusive.

Food security is a situation where all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. For example, Inter-Governmental Authority on Drought and Development (IGAD) Climate Prediction and Application Centre (ICPAC) chronicled approximately 40.4 million people in the Horn of Africa experiencing high levels of food insecurity up from 29 million people at the beginning of April 2022, an increase of 30% in one month [3]. Climate is statistically described as the mean weather, or the long-term variability in both rainfall and temperature, in a given location and place.

The United Nations [4] describes climate change as long-term alteration of the conditions of the atmosphere, that is directly attributed to human activities besides natural climate variability. Conversely, Intergovernmental Panel on Climate Change (IPCC) defines climate change as the alteration in the state of atmospheric conditions statistically determined by the variability in the mean of its properties usually over decades [5]. Climate change affects food quantity, quality and availability besides incidence of plant and animal diseases. This in turn affects farm products through reduction of resources for production [6].

A Representative Concentration Pathway (RCP) is a greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate change [7]. The IPCC studies the carbon cycle separately, predicting higher ocean uptake of carbon corresponding to higher concentration pathways, but land carbon uptake is much more uncertain due to the combined effect of climate change and land use changes [8]. The shortcomings of RCPs are supplemented by Shared Socioeconomic Pathways (SSP) based scenarios further refine the RCPs by mapping societal changes in relation to societal choices influencing government policies on Radiative Forcing up to 2100 SSPs are used to derive greenhouse gas emissions scenarios with different climate policies and economic pathways [9, 10]. SSP-based scenarios were used in the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) for the assessment of past and future climate change in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6).

Taita Taveta County Development Plan (TTCDP), estimates the area under arable farming to be 3,296 hectares to 18, 125 hectares which accounts for small percentage of the county's arable land (TTCDP, 2018). The county experiences two rainy seasons with more rainfall in the highlands than in the lowlands with an annual mean of 650 mm. In this study three agro-ecological zones corresponding to altitudinal zones in the study area were identified: low zone (below 1200 m a.s.l.), middle zone (1200–1700 m a.s.l.), and middle-high zone (above 1700 m a.s.l.).

The beginning and end of rainfall determines the duration of the seasons. These have presented unique patterns with some years exhibiting strong positive and negative *El Nino* Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) events, when shorter or longer than normal length of the growing season is observed. In some instances, the short growing season led to total crop failure (Plat 1: Maize failure in Mwatate Sub-County due to prolonged drought in February- March, 20221) and food deficits, which resulted in hunger and some deaths. sometimes, wet days extend beyond the standard March-April-May (MAM) and October-November-December (OND) rainfall seasons giving long growing periods.

2. Materials and methods

2.1 Description of the study location

Taita Taveta County is located South East of Kenya in the coastal region, approximately 140 km northwest of Mombasa. The County lies between longitudes 37˚ 36˚ E and latitude 2˚40˚ S [11]. The county is categorized as part of the Arid and Semi-Arid Lands (ASALs) of Kenya within the Athi River basin. The county covers an area of 17,083.9 km^2, out of which, 62% is the Tsavo National Park, 895 km^2 comprises the Taita Hills, and the remaining portion consists of small-scale farms, ranches, water bodies and forests [12] (**Fig 1**). The region is characterized by high temperatures and poorly distributed rainfall. The mean annual rainfall in the area ranges from 350 mm-750 mm, with the region around the Taita Hills receiving more rainfall than the lowland areas. The County has a bimodal rainfall pattern with March-April-May

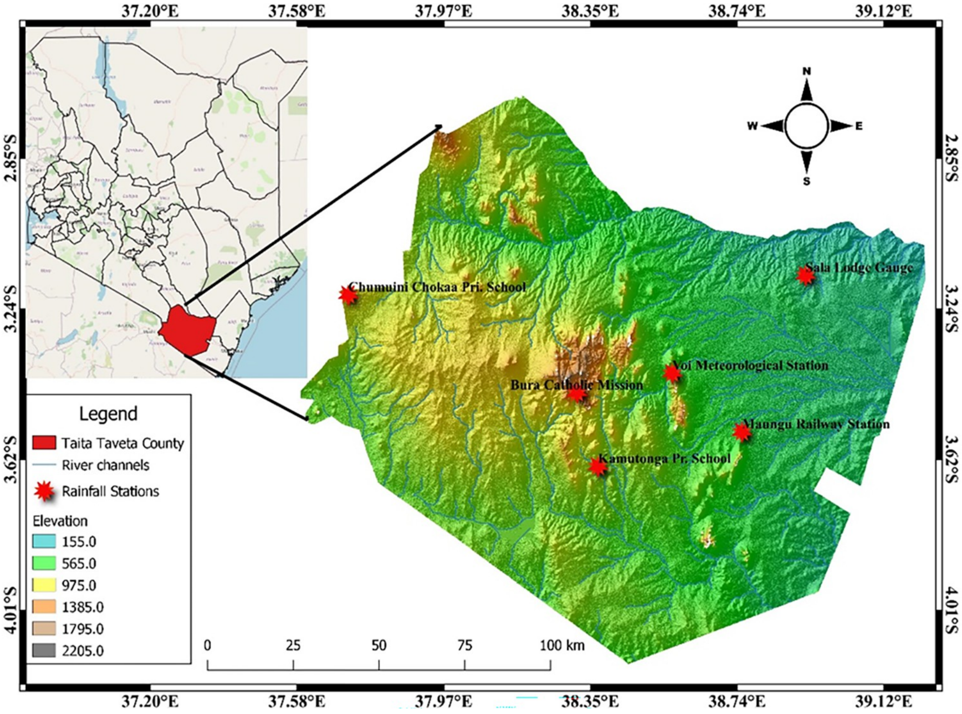

Fig 1.

https://doi.org/10.1371/journal.pclm.0000114.g001

(MAM) having the long rains and Oct-Nov-Dec (OND) with short rains. Rainfall in this region is greatly influenced by the South easterlies from the Indian ocean, which is a source of moisture, and the orographic orientation (presence of the Taita Hills) [13]. Temperature, on the other hand, ranges from at least 21˚C in July-August to about 25˚C in February and March and also in December respectively. There is also a range of 23˚C—27˚C in the plains [14].

The climate is influenced by the Inter-Tropical Convergence Zone (ITCZ) which leads to a bimodal rainfall pattern, with long rains during March–May/June and short rains in October–December, corresponding to the temperature peak [15]. Precipitation and temperature vary across the area. By the mid-21st century, under Representative Concentration Pathway (RCP) 4.5 scenario, the mean annual temperature and mean annual rainfall are projected to rise by 1.8˚C and 72 mm/km^2 $year–^1$ respectively [8], on average across the study area [16] as well as increased variability of season onset and duration especially for short rains.

2.2 Data collection and analysis

The types of data used in this study were observed monthly rainfall, mean surface air temperature from the Kenya Meteorological Department (KMD) for the period 1981–2021. Due to scarcity of data in the area of study, the observed data could not cover the entire region and was supplemented with monthly Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data and Fifth Generation European Centre for Medium-Range Weather Forecasts (ERA5) temperature from European Centre for Medium-Range Weather Forecasts (ECMWF) gridded datasets for the entire study area. This study also used the Coordinated Regional Climate Downscaling Experiment (CORDEX) model outputs to simulate the future climate over the area of study.

A correlation analysis was done to assess the performance of the observed and gridded satellite datasets. There was a high correlation between the observed and gridded datasets (79% for Rainfall, 79 for minimum temperature and 82% for maximum temperature) for the period 1981–2021. Several authors have used CHIRPS and ERA5 datasets as proxy datasets to analyze rainfall and temperature including [17–20]. Table 1 shows the rainfall stations used in this study including their location and distribution.

Table 2 indicates the climate models from the CORDEX-Africa experiment used in the area of study, which were statistically downscaled for a box covering the study area for the period 2022 to 2070, for both rainfall and temperature. Climate projections were derived from the CORDEX-Africa Experiment and were extracted from a box covering Taita Taveta County and the CORDEX model outputs used on monthly time series for the period 1981–2070. Two climate scenarios were also used; RCP4.5 and RCP8.5, with two time slices; 2021–2050 as the present future and 2051–2070 as the medium-term period, which were compared against the baseline period 1991–2020.

Table 1. Rainfall stations used in the area of study.

No.	Station Identification		Location			Distribution			Missing Range (%)
	Name	Code	Lat.	Lon.	Elev. (m)	Start	End	Length (yrs.)	
1.	Maungu RS	9338020	-3.556	38.756	522	1981	2018	37	-
2.	Kamutonga	-	-3.638	38.372	852	1981	2018	37	-
3.	Bura Mission	9338006	-3.450	38.350	1153	1981	2018	37	-
4.	Voi Met station	9338001	-3.4	38.567	556	1981	2018	37	5.4
5.	Salaa lodge	9338038	-3.15	38.917	319	1981	2018	37	-
6.	Chokaa Pr. School	9337143	-3.2	37.717	986	1981	2018	37	-

Source: Kenya Meteorological Department

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Table 2. The CORDEX-Africa regional climate models used in the study.

	GCM Name	Institute Name	Country	Calendar
1.	MPI-ESM-LR	Max Plank Institute (MPI-M)	Germany	Standard
2.	NorESM1-M	Norwegian Climate Centre (NCC)	Norway	365 days
3.	CanESM2	Canadian Centre for Climate Modelling Analysis (CCCma)	Canada	365 days
4.	EC-EARTH	Irish Centre for High-End Computing (ICHEC)	Europe	Standard
5.	GFDL-ESM2M	National Oceanic Atmospheric Administration (NOAA)	USA	365 days
6.	MIROC5	Model for Interdisciplinary Research on Climate (MIROC)	Japan	365 days
7.	HadGEM2-ES	Met Office Hadley Centre (MOHC)	UK	360 days
8.	CNRM-CMS	*Centre National de Resercherches Meteorologiques*	France	Standard
9.	NCC-NorESM1-M	Norwegian Climate Centre (NCC)	Norway	Standard
10.	QCCCE-CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization	Australia	365 days

*Source: (https://esgf-data.dkrz.d)(accessed on March 10th 2021)

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The observed climate data and climate projection outputs were subjected to various trend analyses to obtain the temporal patterns and observe characteristics as discussed in the next subsection.

2.2.1 Time series analysis. Time series analysis was used in this study to establish historical trends and patterns of change in rainfall and temperature datasets over Taita Taveta County. The observed data was plotted against time and the resultant patterns used to identify trends, cycles and periodicities and also seasonality in the climate records (Fig 3). This method has been used by several authors for several purposes including forecasting, interpolation and extrapolation [21–23]. However, several authors have also applied this method in their research works including [24–26]. Significant trends in the time series were tested using Mann Kendal trend test.

Other than the historical climate, time series analysis was used to analyze the trends in the CORDEX climate model outputs over Taita Taveta County. It was also used to assess the future patterns on rainfall and temperature in the time series and identify significant trends and were tested using Mann Kendall trend test as described in the next subsection.

2.2.2 Mann Kendall trend test. Mann Kendall trend test is a non-parametric test that was derived to indicate the direction of a significant trend [27, 28]. It is based on measures of correlation called the Kendall's tau (τ). It is mainly used to detect significant trends in time series that could be due to long term changes in climate datasets. These changes could be due to driving forces such as climate change, land use changes among others [20, 29]. The method has been widely used by other authors including [28, 30–32].

Model performance evaluation was done by evaluating the performance of the models against the observed. A time series analysis was done for all the models including an ensemble of all models. The aim of performing a time series analysis was to identify the best model that performs better and replicates the observed value. Other than time series analysis, several statistics were also done to identify the best model including; correlation analysis, Root Mean Square Difference (RMSD), and Standard Deviation (SD) and model bias. A Taylor diagram was plotted to provide a statistical summary of how well the models mimic the observed. According to Taylor, a Taylor diagram presents how close the patterns march the observed, using the mentioned statistics [33]. Taylor diagrams have been used to evaluate model performance by several authors including [34, 35]. After model ranking, the best model was then subjected time series analysis of both rainfall and temperature and probability distribution function.

2.2.3 Coefficient of Variation (CV). This is a statistical measure of dispersion that is expressed as the ratio of standard deviation to the mean value, and usually expressed as a percentage. It indicates the spatial variation of rainfall and shows the degree of variation of a dataset around the mean. The optimum value should be less than 10 or 0. Values less than 20 are also good. Acceptable ranges could range between 0.2–0.3, while values greater than these are considered unacceptable [36]. High disparity in variables have high values of CV, while lower values have lower disparity within the mean value. CV is indicated by the equation below;

$$\mathrm{CV} = \sigma\mu*100\% \tag{1}$$

In which μ is the mean value and σ is the standard deviation of the dataset.

This study used the coefficient of variation to show the extent of temporal variability of rainfall and deduce the patterns of change in climate.

2.2.4 Spatial analysis. In this method, climate values were spatially presented on graphs and maps to show the distribution and location. Spatial analysis was used in this study to show the distribution of rainfall and temperature both seasonal and annual.

2.2.5 Probability Distribution Functions (PDFs). This method explains the likelihood of a variable to change and also the probability of occurrence of a function at a given point. The skewness of data to the left or right from the mean are the patterns of change in the datasets [37, 38]. It is denoted by f(x) and is given by the equation below.

$$F(x) = 12\ \pi\sigma exp{-}12x{-}\mu\sigma^{2} \tag{2}$$

Where μ is the mean value, $\boldsymbol{\sigma^2}$the variance of the dataset and σ is the standard deviation.

Probability distribution functions were used in this study to assess the patterns of change in the climate projection datasets (rainfall and temperature), and also identify shifts in the mean values, with different time slices. The results obtained were used to assess the impacts of climate change on food systems over Taita Taveta County.

3. Results

This section indicates the observations derived from the underlying study and how it relates similar investigations previously conducted by other scholars. A number of observations were made during the research which led to plausible conclusions.

3.1 Observed spatial characteristics of rainfall and temperature trends

This section presents the results of spatial patterns of annual rainfall and temperature of Taita Taveta. Fig 2A and 2B shows the spatial patterns of the long-term means (1981–2021) of the annual rainfall and temperature over Taita Taveta County. This was purposely done to evaluate the spatial extent and distribution of the annual rainfall and temperature characteristics in the region. The annual rainfall distribution has a variable pattern with rainfall mostly distributed in the western region around Taita Hills. Rainfall starts from the west and decreases to towards the east (**Fig 2A**). The western side receives approximately 900 mm rainfall annually as compared to 500 mm in the lower zone around Voi area and Sala region and the middle zone around Maungu (700 mm). However, much of these rains are influenced by the presence of the Indian Ocean and partly the topography of the surrounding region including Taita Hills. Temperature on the other hand (**Fig 2B**) is not uniform in most locations in the region. Most parts in this area observes a mean of above 20˚C except the western parts around the Taita Hills (approximately 19˚C or lower). The mid zone (Bura and Maungu) has mean temperatures ranging between 21˚C and 23˚C.The hottest region is the northeast around Salaa Lodge with mean temperature above 26˚C all year round.

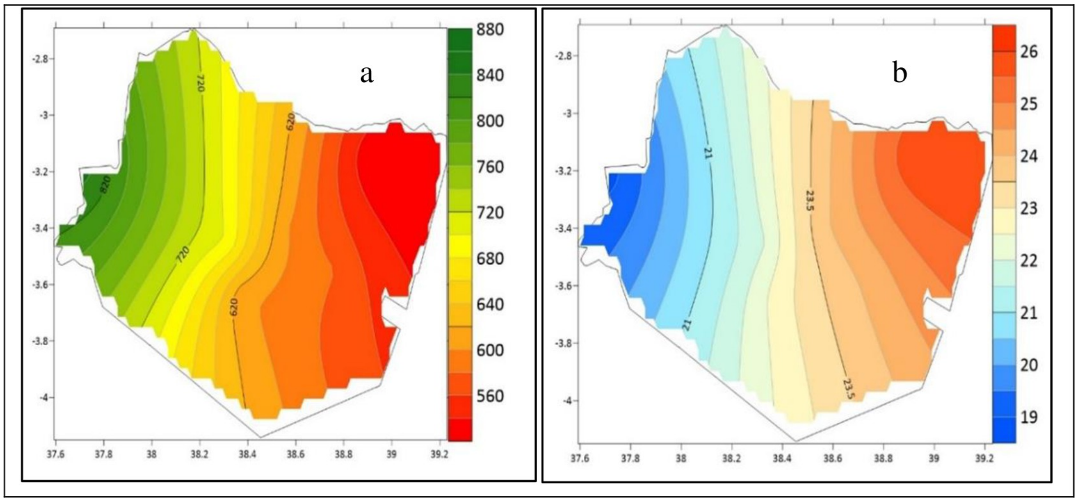

Fig 2.

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3.2 Observed temporal characteristics of rainfall and trends

This section presents the results of temporal patterns of annual rainfall and temperature of Taita Taveta County. Time series analysis was performed on all the stations and trends evaluated. The trends were tested at $\alpha = 0.05$. The trends of annual rainfall and temperature, and their magnitudes for all the stations for the period 1981–2021 obtained by Mann-Kendall and linear regression analysis are shown in Table 3. Analysis of both annual rainfall and temperature revealed increasing trends in all the stations. However, the trends were not statistically significant for rainfall but was significant for all stations for the mean annual temperature. The study findings are consistent with other previous studies conducted over Taita Taveta where the trends of temperature were statistically increasing including [39]. The significant increasing trends in the observed annual temperature is a considerable factor determining the variability of climate in the County.

The total annual rainfall has been gradually increasing over the years, with the mean annual temperatures continuously increasing with a significant trend. Rainfall is also highly variable in this region throughout the year. The months of March and April and October-November observes low variability (0.06), while the month of February observes the highest variability in this region (0.52).

Table 3. Trends in the observed total annual rainfall and mean temperature over Taita Taveta (1981–2020).

Stations	Rainfall			Temperature		
	Annual Mean	Mann Kendall		Annual Mean	Mann Kendall	
		tau	*p-value*		*tau*	*p-value*
1.Chokaa	856.2	0.943	0.486	18.8	0.013	**0.000**
2.Kamutonga	615.0	1.588	0.342	22.7	0.013	**0.000**
3.Maungu	589.8	2.094	0.204	24.2	0.014	**0.000**
4.Salaa	532.8	0.896	0.394	25.9	0.017	**0.000**
5.Voi	609.5	0.708	0.403	23.9	0.017	**0.000**
6.Bura	705.5	0.929	0.422	21.9	0.015	**0.000**
7.Average	650.9	1.195	0.44	22.9	0.015	**0.000**

*Bold values represent statistically significant trends at 95% confidence level

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Table 4. Trends in the observed rainfall, maximum and minimum temperature for DJF, MAM, JJA AND SON seasons (1981–2020) over Taita Taveta County.

	Rainfall			Temperature			
				Maximum Temperature		Minimum temperature	
	Stations	*tau*	*p-value*	*tau*	*p-value*	*tau*	*p-value*
DJF	1.Chokaa	0.233	0.458	0.020	0.052	0.010	0.005
	2.Kamutonga	0.603	0.308	0.018	0.026	0.015	0.000
	3.Maungu	-0.055	0.468	0.025	0.002	0.017	0.000
	4.Salaa	-0.854	0.246	0.029	0.000	0.019	0.000
	5.Voi	-0.157	0.359	0.027	0.001	0.017	0.000
	6.Bura	0.132	0.440	0.024	0.003	0.015	0.000
	Average	**-0.003**	**0.495**	***Mean Temp***		***tau = 0.020***	***p-value = 0.001***
MAM	1.Chokaa	0.405	0.487	0.010	0.261	0.003	0.307
	2.Kamutonga	0.398	0.442	0.005	0.194	0.008	0.029
	3.Maungu	0.228	0.442	0.007	0.148	0.009	0.017
	4.Salaa	-0.021	0.381	0.011	0.087	0.011	0.010
	5.Voi	0.111	0.407	0.010	0.106	0.010	0.008
	6.Bura	0.332	0.433	0.009	0.170	0.008	0.027
	Average	**0.244**	**0.496**	***Mean Temp***		***tau = 0.008***	***p-value = 0.097***
JJA	1.Chokaa	-0.350	0.017	0.030	0.000	0.000	0.268
	2.Kamutonga	-0.039	0.098	0.020	0.001	0.009	0.013
	3.Maungu	0.150	0.331	0.019	0.000	0.010	0.005
	4.Salaa	0.231	0.473	0.020	0.000	0.016	0.000
	5.Voi	-0.072	0.057	0.023	0.000	0.012	0.001
	6.Bura	-0.063	0.065	0.026	0.000	0.009	0.013
	Average	**-0.024**	**0.087**	***Mean Temp***		***tau = 0.016***	***p-value = 0.001***
SON	1.Chokaa	0.335	0.342	0.024	0.005	0.011	0.013
	2.Kamutonga	0.312	0.477	0.011	0.027	0.016	0.001
	3.Maungu	1.435	0.058	0.012	0.037	0.017	0.00
	4.Salaa	1.191	0.179	0.015	0.009	0.019	0.0000
	5.Voi	0.523	0.359	0.016	0.005	0.017	0.000
	6.Bura	0.213	0.495	0.017	0.004	0.016	0.001
	Average	0.668	0.292	***Mean Temp***		***tau = 0.016***	***p-value = 0.001***

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Table 4 indicates the seasonal trends in the observed rainfall and maximum and minimum temperature over the area of study. Rainfall trends were not significant in all seasons. JJA and DJF had decreasing rainfall trends over the years in this region. Rainfall trends for SON and MAM were positive but gradually increasing. However, these trends of rainfall and temperature is a true indication that climate is changing and it will be crucial for the County to take necessary actions including proper adaptation measures.

3.3 Assessment of the performance of CORDEX models in simulating climate over Taita Taveta County

Fig 3 displays a graphical representation of the historical time series of the observed rainfall, the CORDEX RCMs, together with the ensemble average for the period 1981–2005 over Taita Taveta County. From the observations, it is clear that each model has a unique characteristic and pattern over the years. Since graphical analysis is subjective, the CORDEX models were statistically evaluated using the Root Mean Square (RMS), Correlation analysis, Standard Deviation and model bias using a Taylor diagram.

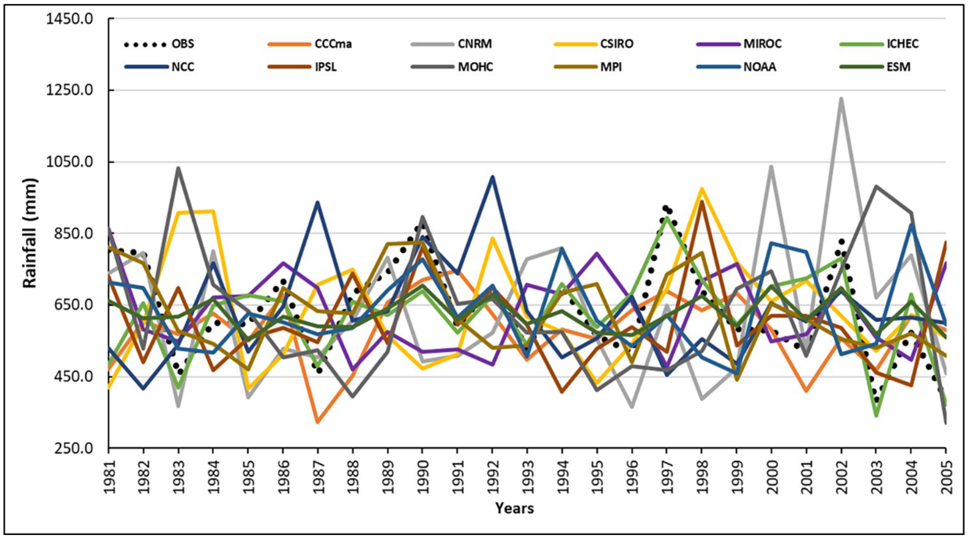

Fig 3.

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Fig 4 shows a Taylor diagram for the CORDEX model performance with the ensemble of all models and the average of the top performing models against the observed over Taita Taveta County for precipitation. From the observations, all the models were positively related to the observation except for QCCCE-CSIRO-Mk3-6-0 (CSIRO) and NorESM1-M (NCC). They failed to reproduce the observed temporal patterns of rainfall trends, hence slightly biased.

Despite the fact that all models had a positive correlation with the observed, the ensemble of the top two models had the highest correlation with the observed, and had higher skill than the individual models in simulating the observed rainfall over the region. QCCCE-CSIRO-Mk3-6-0 (CSIRO) performed the worst of all models while ICHEC-EC-EARTH and MPI-M-MPI-ESM-LR were the best two models that replicated the observed rainfall with a correlation of 69% and 63% respectively (Fig 4). The ensemble of all models had slightly lower correlation (56%). A combination of the top two models presented the highest correlation of all the models (84%). Other studies done within East Africa had similar observations including [34, 40]. From the analysis of the climate models, the ensemble of the top 2 models (ICHEC-EC-EARTH and MPI-M-MPI-ESM-LR) was used to analyse climate projections following RCP4.5 and RCP8.5 pathways.

3.4 Projected future climate patterns

This sub-section presents the results of climate projections and the trend analysis for RCP4.5 and 8.5 over Taita Taveta. The ensemble of the top 2 models (EC-EARTH (ICHEC) and MPI-ESM-LR (MPI) were used for projecting climate by analyzing trends and patterns of distribution.

Fig 5A presents the trend analysis for the future mean annual precipitation while Fig 5B represents trend analysis for mean annual temperature for Taita Taveta County for RCP4.5. Though there is no sufficient evidence to explain for an increasing trend at $\alpha = 0.05$, it is more likely that the projected annual rainfall under this scenario will gradually increase to the end of the year 2070. There will be two major peaks in the years 2022 and 2037 with rainfall above 850 mm over this region. Most of the years will have rainfall ranging between 500 mm-800 mm annually. The years 2026, 2035 and 2065 will have depressed rains. These variable patterns of rainfall call for proper measures to be put in place in the County to avert any impending

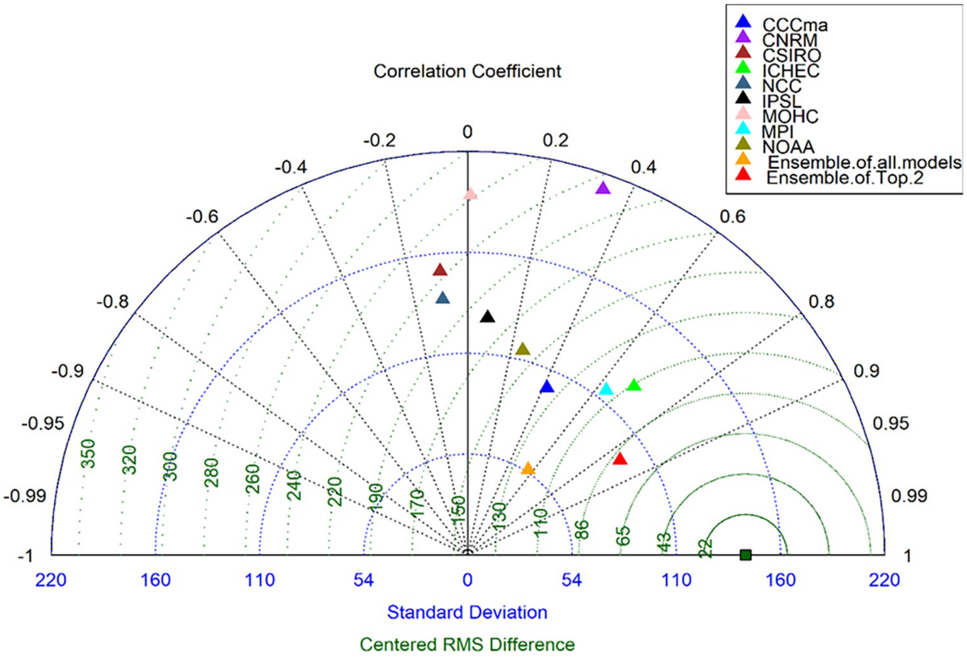

Fig 4.

https://doi.org/10.1371/journal.pclm.0000114.g004

calamity. Temperature on the other hand is expected to have an increasing trend, that is significant at α = 0.05 in the same scenario. All the years will observe an increase until the year 2070. This implies that the future is more likely to be warmer and slightly wetter under this scenario.

In RCP8.5 (**Fig 6A**), the projected annual precipitation depicts an increasing but insignificant trend, at = 0.05. The annual rainfall is projected to gradually increase by the year 2070. The years 2024, 2044, 2048 and 2049 are expected to receive total rainfall below 500 mm. The years 2033/34, 2043, 2054 and 2056 will most likely receive at least 850 mm of rainfall and above. This could be attributed to increase in the mean annual temperature that could lead to high evaporation rates, hence resulting to high cloud formation due to the presence of the Taita Hills, and eventually resulting in enhanced rainfall amounts. Most years will have rainfall within the normal range (500–800 mm). Temperature under this scenario is projected to increase significantly until the end of the year 2070 (Fig 6B). The mean annual temperature will be approximately 24˚C by 2050 and projected to be higher by 2070. The future under Representative Concentration Pathway (RCP8.5) is therefore projected to be warmer and slightly wetter. Thus, the variable patterns of weather call for proper measures to be observed including strategies and modalities to effectively manage this scenario over Taita Taveta County.

3.5 Climate patterns over Taita Taveta County

Fig 7 indicates rainfall and temperature distribution for RCP4.5 and RCP8.5. Three climate periods were used to evaluate changes and patterns of change in the future climate; (1991–2020) which was also used as the baseline climate period, 2021–2050 as the present future period and 2051–2070 as the mid-century climate period. There is a likelihood of a positive shift in the total annual rainfall and mean temperature in both scenarios, and in all climate periods. High temperatures will most likely be due to increased global warming, which in turn would lead to high rates of evaporation, eventually leading to high rainfall occurrence hence positive shifts until the year 2070. In RCP4.5 **(Fig 7A),** rainfall will shift from a mean of 643.31

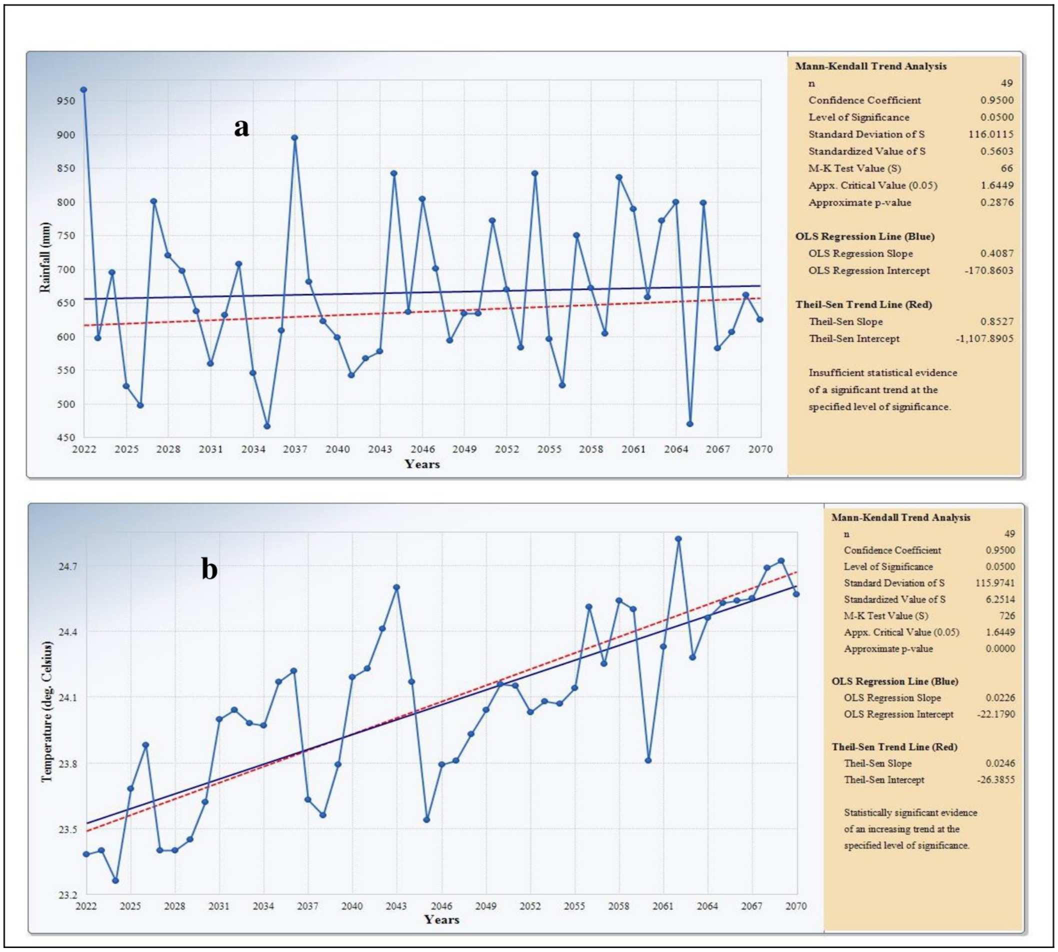

Fig 5.

https://doi.org/10.1371/journal.pclm.0000114.g005

mm in the baseline to 655.85 mm (+1.9%) by 2050 and then a further increase to 680.66 mm (+3.8%) by 2070. Temperature in this scenario will progressively increase with reference to the baseline scenario. From a mean of 22.9˚C in the baseline, temperature will shift to an average of 23.8˚C by 2050 (+0.9˚C), and further to 24.3˚C by the end of 2070 (+1.4˚C) from the baseline respectively (**Fig 7B**).

In RCP8.5 (**Fig 7C**), there will also be a positive increase from a mean of 643.31 mm of rainfall to a mean of 648.56 mm by the end of 2050 (~+1%), and a further shift to 705.56 mm by the end of 2070 (+9.6%), with reference to the baseline mean (1991–2020). In this scenario, temperature will increase from a mean of 22.9˚ C to a mean of 24.1˚ C (+1.2˚ C) by 2050, and further to 25.2˚ C (+2.3˚C) by the end of 2070 respectively (**Fig 7D**).

3.6 Test of significance for the climate periods

Table 5 shows the results from the Wilcoxon Signed Rank test for the climate period from 1991–2070. Climate period 1 was the baseline (1991–2020), while climate period 2 (2021–2050) and climate period 3 was the year 2051–2070. All the climate periods had positive and non-significant trends, in all climate periods in both scenarios except for the transition between period 1 to 3 in RCP8.5 for rainfall. Temperature on the other hand had significant shifts in the means between all climate periods, with increasing trends for both RCP4.5 and

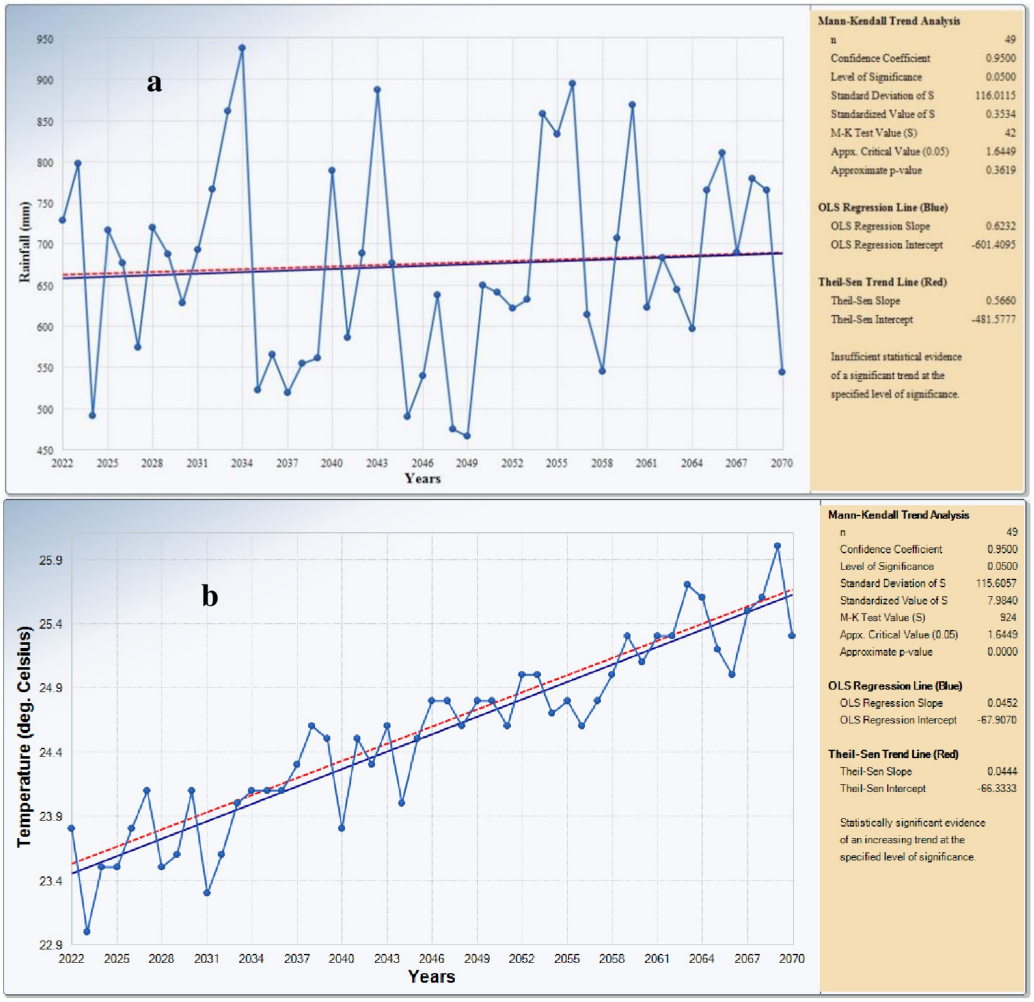

Fig 6.

https://doi.org/10.1371/journal.pclm.0000114.g006

RCP8.5. The positive and significantly increasing temperature trends with variable rainfall patterns will greatly impact the food industry.

3.7 Projected impacts of climate change on food systems

The impacts of climate change on food systems are projected to increase, become complex and variable (Table 6). In RCP4.5, rainfall is more likely to increase by at least 1.9% by 2050 and 3.8% by 2070, while in RCP8.5, rainfall will increase by approximately 1% by 2050 and 9.6% by the end of the year 2070. Temperature will significantly increase by +0.9˚C by 2050 and by +1.4˚C by the year 2070 in RCP4.5. RCP8.5 scenarios will observe the highest shifts in the mean annual temperature changes with 1.2˚C temperature increase by the year 2050 and 2.3˚C temperature change by the end of the year 2070. RCP8.5 is therefore projected to be much warmer and wetter. These changes under different climate change scenarios will greatly impact on several sectors within the county. Other than changing the hydrological cycle within the region, several sectors such as agriculture, health, tourism and economic sectors will be affected.

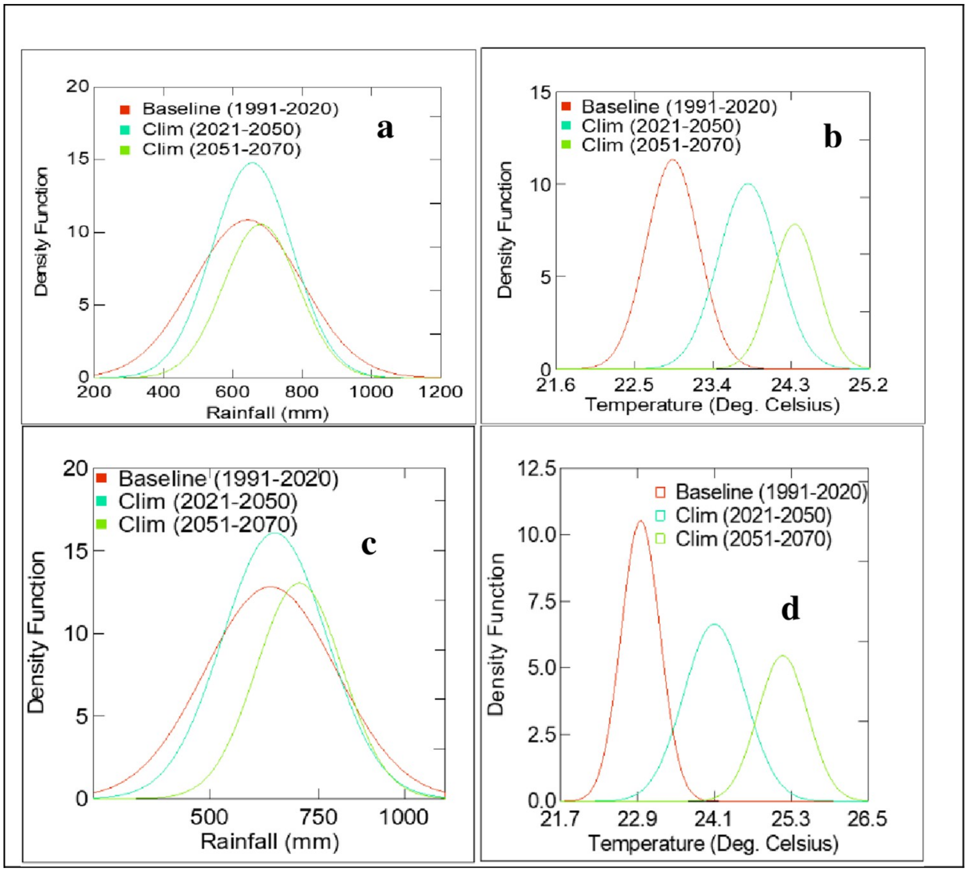

Fig 7.

https://doi.org/10.1371/journal.pclm.0000114.g007

4. Discussion

The results of this study show trends of climate change and projections of future climate in the study location and other areas in the Country and the region with similarities in climatic conditions.

From the observations, the spatial patterns of the long-term means (1981–2021) of the annual rainfall and temperature over Taita Taveta County, it was expected that annual rainfall distribution would exhibit a variable pattern with rainfall mostly concentrated in the western region around Taita Hills and neighboring highlands with a marked decrease towards the east (Fig 2A and 2B). This could be attributed to the influence of the Indian Ocean and partly the

Table 5. Wilcoxon sign rank test for significance of the climate periods.

		Rainfall		Temperature	
	Climate period	***p-value***	**Remarks**	***p-value***	**Remarks**
RCP4.5	1 and 2	0.614	Not Significant	0.000	Significant
	1 and 3	0.057	Not Significant	0.000	Significant
	2 and 3	0.351	Not Significant	0.000	Significant
RCP8.5	1 and 2	0.688	Not Significant	0.000	Significant
	1 and 3	0.033	Significant	0.000	Significant
	2 and 3	0.370	Not Significant	0.000	Significant

https://doi.org/10.1371/journal.pclm.0000114.t005

Table 6. The likely projected impacts of climate change on food systems in Taita Taveta County.

Projected Impact	Likely Impact on Food System
Projected Temperature Variations	Withering and water stress for agricultural production, Increased water demands for agricultural production, Loss of crop and livestock productivity, Increased yields in colder areas especially in the Taita highlands, Reduced yields in warmer environments like in the lower lands near Voi town and Sala Lodge, Increased pests and disease outbreaks, Reduced productivity of aggregators and high incidences of pests and diseases, Value addition through processing for longer shelf life of farm products, Predispose farm products to high perishability reducing shelf life, Damage of food products on transit from production, Extra energy utilization for maintaining products in wholesome state for distribution, Damage of food products thus lowering the grade and price of commodities, Lower consumption rates of the food products
Rainfall Variability	Fluctuations in levels of production, Low crop yields and reduced nutrient content in soils, Water stress and inability to cultivate, Frequent attack of pests and diseases from increased rainfall, Damage to Crops, soil oversaturation, and Soil erosion and land degradation, Fluctuation in amount of food products to be aggregated, Reduced number and quantity of products to be processed i.e., it will dictate the amount of food products for processing and also products available for storage, Surplus in produce from increased rainfall thus increased transportation, Damage to infrastructure such as roads following increase in rainfall amounts, Destruction of food distribution channels, Effect on the quality of food products, Fluctuation/ volatility in market prices, Distort the quality and yield of food products, Affects consumption rates and patterns
Climate-induced Extreme Events	Floods and frost that will damage the crops leading to low or no yields and also damage aggregation channels, Heat islands or waves which may increase the incidences of crop pests and diseases, Frosts which may necessitate temperature regulation using technologies which may in turn lead to GHG emission, Floods that may cut off supplies of food products from processing industries or other complementary inputs into the processing industries, damage of storage and transport infrastructure and also, Minimization of products to be distributed and also damages the distribution system, Damage of marketing channels and increases in purchase prices thus reducing access by consumers, Lower GDP and also lower purchasing power of vulnerable populations, Increases in the market prices thus reducing access by consumers, Diminish of yields and altered primary production, Increased pests and pathogens leading to infectious diseases characterized by diarrhea, Prolonged droughts which may lead to inadequate produce to be aggregated and also make storage facilities to be more susceptible to disasters such as fires, Droughts may expose the systems to fire risks as well as minimizing products to be transported, Increased prices in food commodities, Price volatility hence lower purchasing power, Altered nutrient supply and nutrition status hence malnutrition to vulnerable ages

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topography of the surrounding region including Taita Hills and the neighboring Mount Kilimanjaro and the Pare Highlands.

Fig 2B illustrates the spatial distribution of the mean annual temperature over the County. It depicts variation in temperature across the study area. Most areas in the county experience mean temperatures above 20˚C except the western parts around the Taita Hills with approximately 19˚C or lower. The mid zone around Bura and Maungu experience mean temperatures ranging between 21˚C and 23˚C.The hottest region is the northeast around Salaa Lodge with mean temperature above 26˚C all year round. These observations are in agreement with other studies done in the region including [39, 41, 42].

4.1 Projected impacts of climate change on food systems

The impacts of climate change on food systems are projected to increase, become complex and variable. In RCP4.5, rainfall is more likely to increase by at least 1.9% by 2050 and 3.8% by 2070, while in RCP8.5, rainfall will increase by approximately 1% by 2050 and 9.6% by the end of the year 2070. Temperature will significantly increase by +0.9˚C by 2050 and by +1.4˚C by the year 2070 in RCP4.5. RCP8.5 scenarios will observe the highest shifts in the mean annual temperature changes with 1.2˚C temperature increase by the year 2050 and 2.3˚C temperature change by the end of the year 2070. RCP8.5 is therefore projected to be much warmer and wetter. These changes under different climate change scenarios will greatly impact on several sectors within the county. Other than changing the hydrological cycle within the region, several sectors such as agriculture, health, tourism and economic sectors will be affected.

Whereas food security denotes "availability, access, utilization and stability" of sufficient quantities of quality foodstuff, a food system is a chain of interlinked activities and processes from inception or establishment of food items to ultimate consumption or disposal of the products and wastes. In the study location, the most critical aspect of the food system is food production. This is in partial compliance to [43] who views global food system as the "production, processing and distribution of food throughout the world". Thus, global food system comprises various industries involved in conventional production, processing and distribution of food in the world [5].

In Taita Taveta, however, a food system entails on-farm production, food acquisition through purchase, acquisition of food supplies from relatives, friends or donations as food aid; processing and distribution of food within the population. Food acquisition is often supplemented with importation of additional supplies across Taveta border at Holili as revealed by Focused Group Discussion (FGDs) at Chokaa Primary School and Key Informant Interviews (KII) with Red Cross, market aggregators and National Drought Management Authority food monitors. The location of Taita Taveta at the Kenya-Tanzania border enhances importation of food items due to the comparatively lower cost of production and existence of palatable varieties across the border. Improved road infrastructure also facilitates movement of food across the border to Taita Taveta County.

Whereas Representative Concentration Pathway (RCPs) were explicitly designed for the climate modelling community to explore the effects of different emissions trajectories or emissions concentrations leading to various Radiative Forcing values.

The variable pattern of the annual rainfall distribution in Taita Taveta County (Fig 2A) shows that rainfall is mainly concentrated in the higher altitude western region around Taita Hills and decreases towards the east. The western side receives approximately 900 mm annually whereas the middle zone around Maungu receives 700 mm and the lower zone around Voi area and Sala region receive about 500 mm. Much of these rains could be attributed to South-Easterlies from the Indian Ocean and partly to the topography of Taita Hills and the surrounding areas.

Food systems mainly depend on prevailing climatic conditions as demonstrated by various studies. Climate change impacts on various food subsystems, albeit, differently. For instance, prolonged drought affects production by causing water stress in crops and water deficit and dehydration in livestock. Similarly, high temperatures with low moisture would lead to water stress in crops due to high evapotranspiration and dehydration in livestock. Conversely, high rainfall leads to moist conditions which may predispose crops to rampant pest and disease incidences. Low rainfall leads to insufficient moisture and hence poor crop yields and ultimately escalate food prices, reduced livelihoods unemployment and lowered income for market-reliant households [44, 45].

Erratic climate cause floods and prolonged drought in low and medium altitudes leading to heavy crop damage, livestock deaths and human displacement whereas there is marked frost in high altitude areas which cause losses in some crops. Extreme climate events also affect aggregation, marketing, farmer livelihood options and consumer incomes indirectly by damaging storage and transport infrastructure and thus raising the cost of food. The situation may be worsened when some areas are rendered unsuitable for farming as a result of increased warming [46]. Erratic climate such as droughts, floods, wild fires and delayed onset and duration of rainy seasons can directly affect agricultural production, condition of roads used to supply food to consumers and prevent farmers from accessing farm inputs [47]. In addition to common challenges of erratic climate events identified, there is escalating human wildlife conflict in the study area because prolonged droughts lead to shortage forage and water and this drives wildlife to the villages in search of water and food. They thus forage on crops and also destroy water reservoirs in human settlements. S1 Fig shows the impact of prolonged drought in Mwatate Sub-County of Taita Taveta County in JFM 2021 with devastating crop failure.

Frequent extreme weather events including floods, droughts, heat waves, persistent conflict, economic shocks, displacement and insecurity trigger food security have been described by Inter-Governmental Authority on Drought and Development (IGAD) as being rife in the Horn of Africa, leading to which [48]. Weather parameters impacting on crop production such as mean precipitation and temperature greatly manifest in production but this also depends on the type of crop [49]. Elevated high temperatures and variable rainfall patterns normally affect the agricultural sector in most developing countries since they mostly depend on rain-fed production [8]. At least 30% of the land in Africa is estimated to be under cereal production, and 67% of maize produced is from low and mid latitude countries. Sub-Saharan Africa is the worst affected and with very low produce due to changes in climate patterns [5, 50, 51].

Climate scenarios taking the form of Climate Erraticism manifest in projected increase in temperature and variable rainfall patterns. This could be detrimental to the food sector by disrupting food availability, reduced access to food and also affect food quality in some circumstances. It reduces crop yields while encouraging weed and pest proliferation due to their competitive edge. Alternating extreme drought with extreme wetness and floods are often witnessed in Taita Taveta County leading to conditions similar to climate whiplash of America's South West between 2011 and 2016 in 2016–2017 [47, 52], observes increased alternating climate extremes such as flood and drought, rapid transitions and ensuing risks to destruction. Future weather whiplash would cause intense drought year followed by record rains that don't allow planting or that wash crop nutrients into waterways and this ultimately leads to yield reductions, crop damage, and crop failure [53, 54]. Warmer conditions elicit flash drought fire outbreaks [55, 56].

Climate change, however, may have some beneficial effects. Notable among the positive effects of climate change is enhanced rainfall (Figs 6A and 7A) which, albeit causing floods, leads to sufficient water agricultural production especially if practitioners leverage and optimize on flood waters. The floods could be captured and stored in household ponds, water pans and earth dams for long-term utilization as observed in the study area. High temperatures (Figs 6A and 7B) also create conducive environment for crop production due to faster growth and maturity period. High temperatures also facilitate forage growth and, by extension, livestock production indirectly through enhance fodder production. Likewise, climate whiplash in South West USA triggered bumper production of grasses and other vegetation followed by a combustible condition leading to severe wild fires sweeping vast areas in California in 2017–2018 [52].

In the study area, farmers leverage on floods to invest in flood-based livelihoods which involve, among other initiatives, capturing of flood waters and storing in in ponds for aquaculture and other uses with appropriate management practices. These conditions could suit crops and livestock tolerant to warmer, wet climatic conditions including aquaculture.

Taita Taveta County farmers have adopted several methods to manage the ramifications of climate change in order to improve their farm production [57]. Observed time series for onset and cessation of rainfall in the County for 1981–2018 indicates that the mean length of the March to May rainfall season generally estimated at 31 to 40 days while the October to December season is generally longer ranging from 51 to 80 days with some areas in the county experiencing as many as 90 days reverberates the views of previous scholars such as [14].

5. Conclusions

December, January, February (DJF) has the highest range in the mean temperature compared to other seasons (24.3˚C) and this coincides with the short rain season which is also the wettest season of the year. Temperature in the County varies with altitude with the coolest region being the western side around the Taita Hills and the eastern side being the hottest. Climate models predict future increased warming. Results from this study predicts a significant future increase in temperatures over Taita Taveta County both for RCP 4.5 and RCP8.5. High temperatures cause warming of the atmosphere which also makes it conducive for thriving of pests and disease-causing pathogens which may impact on livestock and human beings. In spite of observed high temperatures in low altitude zones leading to conducive environment for rapid growth and ripening of cereal crops and fruits beside enhanced growth and maturity of animals.

According to Wilcoxon Rank Test for Significance, there is projected insignificant future increase in rainfall in the study area. Rainfall amounts and distribution varies across the County with the highest being recorded in Taita Hills in the west and lowest in the North–eastern part of the County. Climate change portrays both negative and positive consequences and therefore the need to adapt to and mitigate negative consequences while leveraging on the positive impacts. The high-altitude zone which lies on the west side of the county, around Taita Hills, receives more rainfall which decreases towards the east and north-Eastern side. Erratic rainfall may also damage, storage and transport infrastructure among other negative effects.

Three most outstanding projected impacts of concerns for the study location and the region as a whole based on the warming trend observed include alternating prolonged droughts and flush floods and wildlife damage which could lower agricultural and livestock production. Floods may stem from heavy rainfall and hence loss and damage of crop and livestock fields, transport and storage infrastructure among other investments. It is therefore necessary to prepare inhabitants for adaptation to probable erratic climate changes. Notable positive climate change impacts from this study included bumper harvests immediately following enhanced rainfall years especially after *El Nino*. Although climate change impacts on the whole range of food sub-systems and their value chains ranging from production, aggregation, transport, distribution, consumption and disposal of food wastes, the most critical subsystem is production.

6. Recommendations

Based on the findings from this study and the challenges that arose, the following are the general recommendations for further research work, to the policy makers, the community, the County and the country as a whole:

1. The need for communities to adapt the scientific early warning systems and blend it with the traditional system to leverage on the synergies to address or abate any climate adversities;
2. From the findings obtained in this study the researchers ought to install new and revitalize dilapidated meteorological centres in Taita Taveta County and Kenya as a whole to enhance capture and disseminate climate data, limit the use of gridded data and enhance the use of early warning systems;

3. Researcher should develop new applications and enhance the capacity of farmers on adoption of climate smart technologies in future.

Supporting information

S1 Checklist. FGD checklist.
(PDF)

S1 Text. KII.
(PDF)

S2 Text. KMD.
(PDF)

S1 Data. CORDEX data projections.
(XLSX)

S2 Data. Data enum.
(JPEG)

S1 Fig. Impact of prolonged drought on maize production.
(TIF)

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