



Climate change and cocoyam (*Colocasia esculenta* (L.) Schott) production: assessing impacts and potential adaptation strategies in Zimbabwe

Abel Chemura¹ · Dumisani Kutuywayo² · Danisile Hikwa² · Christoph Gornott^{1,3}

Received: 5 May 2020 / Accepted: 9 June 2022 / Published online: 27 July 2022
© The Author(s) 2022

Abstract

Tropical root and tuber crops such as cocoyam (*Colocasia esculenta* (L.)) are important for food security and livelihoods and yet neglected in climate change impact studies and large-scale crop improvement programs. The aim of this study was to apply the maximum entropy modelling approach to assess production potential for the orphan crop cocoyam under current and projected climatic conditions by 2050 and 2070 in Zimbabwe. A robust model fit was achieved ($AUC > 0.9$) with variable importance showing that precipitation-related factors were most important in determining the suitability of cocoyam. About 4.3% of the country is suitable for cocoyam production in Zimbabwe under current climatic conditions with the most suitable areas in eastern districts of Chipinge, Chimanimani, Mutare, Mutasa, Nyanga and Makoni. By 2050, model means project a decrease of 6%, 9%, 10% and 15% under RCP2.6, RCP4.5, RCP6.0 and RCP8.5, respectively. More drastic decreases are projected by 2070 with almost a quarter (23%) of the current suitable areas having lost their suitability for cocoyam production. There is a general model agreement in the direction of impacts except for RCP2.6 where CCSM4 model projects increases in suitability for cocoyam in the country while other models project decreases. We find that regulating canopy microclimate variation increases potential for cocoyam production under climate change and can be implemented to ensure resilience of cocoyam production systems. Therefore, stabilizing or improving orphan crops systems will substantially contribute to local food security and reduction of malnutrition especially during the lean season.

Keywords Cocoyam · Roots and tubers · Neglected crops · Crop suitability · Agroforestry

✉ Abel Chemura
chemura@pik-potsdam.de

¹ Potsdam Institute of Climate Impact Research, a Member of the Leibniz Association, Potsdam, Germany

² Department of Research & Specialist Services Head Office, Harare, Zimbabwe

³ Agroecosystem Analysis and Modelling, Faculty of Organic Agricultural Sciences, University of Kassel, Kassel, Germany

1 Introduction

Root and tubers are the second most important group of food crops in the developing world after cereals, contributing to diets of over 2 billion people across the tropics and subtropics with annual production of about 800 million tons (FAOSTAT 2016; Taylor et al. 2019). This is because these roots and tubers are preferred as traditional crops favoured for their adaptability to local environs, their ability to fit long-held culinary practices and dietary requirements and their compatibility with other crops in common crop diversity systems (Ray and Sivakumar 2009; Valenzuela and Defrank 1995). They are thus important for the calorie and nutrient supply of the rural populations and thus contribute to reduce food insecurity and malnutrition (Myers et al. 2017; Tadele 2019). These include cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), cocoyam (*Colocasia esculenta*), yautia (*Xanthosoma* spp.) and yams (*Dioscorea* spp.). These roots and tubers are however under researched (orphan crops) as they lag behind in terms of genetic diversity, biotechnology applications and limited scientific evaluations of adaptability (Ganança et al. 2015; Mabhudhi et al. 2019). As a result, many root and tuber crops such as cocoyam are classified as a neglected and underutilized crops (Singh et al. 2012; Tumuhimbise 2015).

Cocoyam (also referred to as arroid or arrowroot) is a perennial herbaceous plant with thick, fleshy and creeping roots and long white fibres belonging to the monocotyledonous family Araceae and are a staple in many parts of the developing world (Ray and Sivakumar 2009). Cocoyam is one of the most important traditional tropical root crops, being the fifth most produced root crop in the world with over 12 million tons of production annually (Taylor et al. 2019). It is mainly grown in tropical Africa, China, New Guinea and the Pacific islands for its starchy corms, although leaves and flowers are also consumed as vegetables or medicines (Akwée et al. 2015; Kaushal et al. 2015). In Africa, the two most commonly cultivated species are *Colocasia esculenta* and *Xanthosoma sagittifolium*, which are grown extensively (Eneh 2013; Opoku-Agyeman et al. 2004).

Cocoyam has a high moisture requirement, growing well in margins of wet fields and along streams (Ganança et al. 2015). In the region cocoyam production systems are based on small but high-density production systems in lowlands, on slopes or under trees in the fields. It prefers high rainfall areas (> 1,500 mm) with a uniform distribution throughout the year (Mwenye 2009). According to Lim (2015), low rainfall reduces corm growth as intermittent moisture stress causes low yields, dumb-bell-shaped corms and of poor quality. Cocoyam does well in moist, but well-drained soil that is rich in organic humus and can tolerate shallow occasional flooding (Kaushal et al. 2015; Matthews 2010; Rees et al. 2012). In terms of temperature, cocoyam is adapted to warm temperatures above 21 °C and minimum temperatures that do not fall below 10 °C (Lim 2015). It is therefore more cold hardy than many of its relatives by tolerating temperatures down to 10 °C, but freezing temperatures damage the leaves and results in yield underperformance (Lim 2015; Raemaekers 2001). The crop is a long-season crop taking between 180 and 300 days to mature (FAO 1994).

To meet the temperature and rainfall requirements, cocoyam is often planted under permanent plantations like banana, coconut, citrus, oil palm, cocoa and other agroforestry systems in many countries. According to Taylor et al. (2019), the agro-ecological range of cocoyam will shift under climate change because the crop prefers wet, humid environment with little to no ability to tolerate drought. This was confirmed by a modelling study by Kodis et al. (2018) who concluded that potential for cocoyam production will be drastically reduced in Hawaii especially under high emission scenarios. This is especially concerning

given that generally roots and tubers have received very little attention from researchers, extensionists and policy makers who invested much of their efforts and resources on grain crops and grain-based products (Dhliwayo 2002; Rees et al. 2012). This lack of consideration of important crops such as roots and tubers therefore increases the risk of “hidden hunger” by considering calories from cereals and forgetting important nutrients from other crops (Gödecke et al. 2018; Müller et al. 2014).

The aim of this research was therefore to use an environmental niche modelling approach to determine agricultural suitability of cocoyam under current and projected climatic conditions in Zimbabwe. Understanding agricultural suitability and potential productivity of crops such as cocoyam is important for many scientific applications and policy decisions. The development of niche-based models has enabled many applications to predict geographic outcomes from environmental data including in determining agricultural suitability (Heumann et al. 2011). In this case, suitability is defined as the ability of an area to sustain the production cycle from planting to harvesting as well as achieving required quality at prevailing production costs. The specific objectives are (i) to establish the edaphic and bioclimatic factors that determine suitability for cocoyam production, (ii) determine suitable areas for cocoyam production under current and future climate change in Zimbabwe, (iii) identify the suitability change hotspots for cocoyam under climate change and (iv) evaluate the potential of adaptation measures to buffer losses in suitability. This is important in identifying potential production areas, increasing production areas for cocoyam from identified potential areas and ensuring resilience of the orphan crop production.

2 Data and methods

2.1 Crop location data

The crop location data for cocoyam were obtained from field points from production areas produced by public extension services, the Agricultural and Technical Extension Services (AGRITEX) in 2014/2015 season. AGRITEX is the mandated organization under the Ministry of Agriculture (MoA) for collection and reporting of agricultural production data in Zimbabwe. These are based on production reports from a network of field extension staff across the country and mark a place to have the crop, if an extension worker in a Ward (the smallest geographical operational area of an extension worker) reports its presence and hectareage. The maps were geo-referenced, with points created to mark the centre of the reported production area. The distribution of the points is shown in Fig. 1.

2.2 Environmental variables

Climatic, soil and topographic variables were used in modelling the suitability of cocoyam in Zimbabwe. Bioclimatic variables used in the study were obtained from the WorldClim database (<http://www.worldclim.org>) (Hijmans et al. 2005). A total of 19 bioclimatic variables produced from analysis of trends of monthly values of precipitation and temperature throughout the year to produce agronomically and ecologically useful variables for primary production are available from the database. However, some of these variables are collinear and therefore cannot be used in the same model. A variable selection routine using the variation inflation factor (VIF) was therefore implemented where in cases where the VIF was above 10, only one agronomically

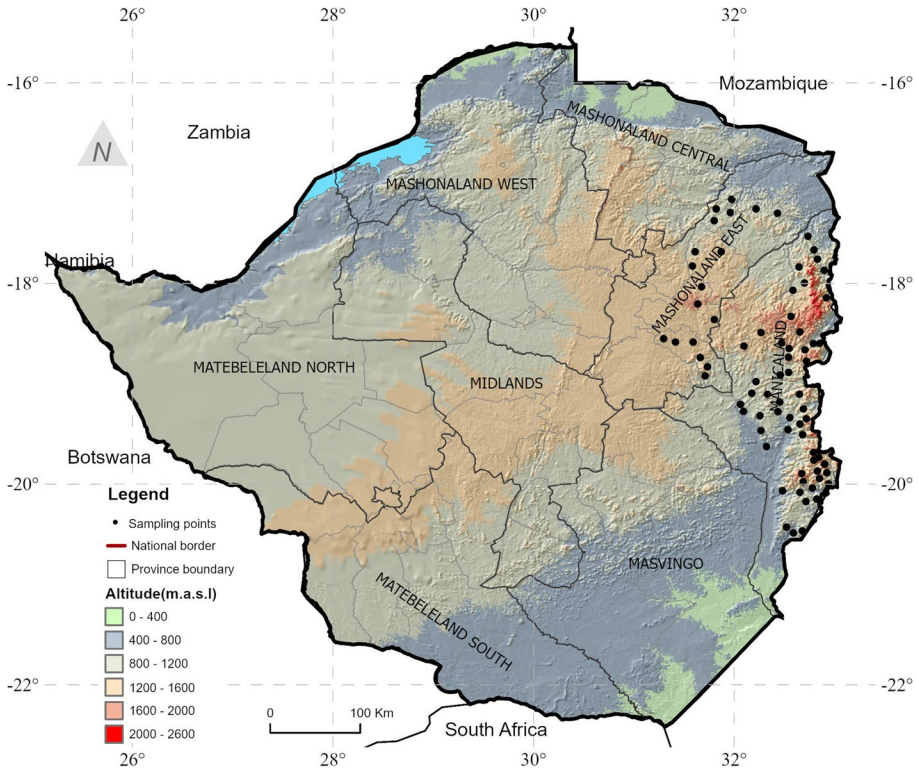


Fig. 1 Maps showing the location of the sampling points that were used in modelling the suitability of cocoyam in Zimbabwe. The background map shows the altitude in meters above sea level (m.a.s.l)

deemed important variable was retained based on the long-season nature of the crop. Six bioclimatic layers were finally used because they were independent and are related to the major climatic factors that determine perennial crop production (Table 1). The bioclimatic variables used were annual mean temperature (Bio1), temperature seasonality (Bio4), mean temperature of the wettest month (Bio8), total annual precipitation (Bio12), precipitation seasonality (Bio15) and precipitation of wettest quarter (Bio16).

Table 1 Description, units and source of environmental (bioclimatic, topographical and soils) data used in the modelling of cocoyam suitability in Zimbabwe

Code	Description	Units	Source
Bio1	Mean annual temperature	°C	WorldClim
Bio4	Temperature seasonality ($\sigma \times 100$)	%	WorldClim
Bio8	Mean temperature of wettest quarter	°C	WorldClim
Bio12	Total annual precipitation	mm	WorldClim
Bio15	Seasonality of precipitation ($\sigma \times 100$)	%	WorldClim
Bio16	Precipitation of wettest quarter	mm	WorldClim
Soil	Soil type (subfamily)	Class	SG dept
DEM	Altitude data	m	USGS

These climatic layers were available in 1km² grids and are interpolated from weather station recordings.

Soil type was also added to the modelling as an important agronomic variable. The soils data were derived from two 1:100,000 scale soil map of Zimbabwe obtained from the Surveyor General's Department based on detailed description of the soils of Zimbabwe by Nyamapfene (1991). The soils of Zimbabwe are divided into 8 groups which are lithosol, regosol; vertisol, siallitic, fersiallitic, paraferallitic, orthoferallitic and sodic (Supplementary Information 1). The digital elevation model (DEM) was used to derive elevation data for the whole country. The DEM was obtained from global USGS (GTOPO30) global dataset at 1 km resolution. We did not include socio-cultural predictors such as population density or settlements in our modelling because we assumed that although there is a specific current production area for cocoyam in Zimbabwe, the crop has a national potential and as such all available suitable areas can be used to produce the crop (except protected areas and urban areas where this is not possible).

2.3 Modelling approach

Bio-climatic envelope models are a set of tools that are used to determine the potential distribution of species based on a set of known occurrences and climatic data (Austin 2007; Elith et al. 2011). Crop suitability is a measure of the biophysical characteristics of an area to meet crop production requirements at current or expected production levels (Chemura et al. 2020a; Srinivasan et al. 2019). These models are used for agricultural crops based on the understanding the greater share of major crop production is still influenced by natural climatic factors in many countries. Crop suitability models have been applied in modelling agricultural crops such as cassava (Heumann et al. 2011; Jarvis et al. 2012), maize (Estes et al. 2013; Holzkämper et al. 2013; Nabout et al. 2012), sorghum (Evangelista et al. 2013), common beans (Ramirez-Cabral et al. 2016; Taba-Morales et al. 2020) cocoyam among many other crops (Beck 2013). The outputs of crop suitability models include maps and therefore they are important in identifying climate change impact hotspots that require adaptation measures.

The maximum entropy (Maxent) approach has been used in this study. Maxent is a general purpose environmental niche modelling approach that is capable of making reliable predictions using information from sites where the modelled species is known to occur (Phillips et al. 2006). Maxent estimates a target distribution by finding the most spread out or closest to uniform distribution, subject to a set of constraints that represent the known information about the target distribution (Elith et al. 2011; Phillips et al. 2006). Unlike other modelling approaches, Maxent is a learning model and data is fit using linear and non-linear functions and different functions can be hinged together (Heumann et al. 2011). Maxent has been found to be more accurate when applied to “presence only” data than other approaches and is capable of providing reliable distribution from relatively smaller sets of data (Elith et al. 2011; Hernandez et al. 2006; Stokland et al. 2011). Based on these characteristics, Maxent was chosen as the best modelling approach to perform crop suitability assessments for cocoyam in Zimbabwe under current and future climatic conditions.

2.4 Model settings, evaluation and data analysis

Maxent version 3.3.3 k was used for the modelling (Phillips and Dudík, 2008; Young et al. 2011). We controlled the complexity of the Maxent model by selecting best input

parameters and model settings to reduce model overfitting. The model calibration, choice of final model and evaluation were done using the “ENMeval” r package (Muscarella et al. 2014), and the “rmaxent” library. The regularization multiplier was applied to control the model complexity by assigning a penalty for each additional term included in the model (Anderson and Gonzalez 2011; Warren and Seifert 2011). The optimal model complexity was determined from combinations of 5 values for the Maxent regularization parameter from 0.5 to 4 at intervals of 0.5 and 6 different individual and combined feature classes (L, LQ, H, LQH, LQHP, LQHPT; where L=linear, Q=quadratic, H=hinge, P=product and T=threshold) were evaluated and together with the optimization of regularization gain resulted in 768 models (Cuervo et al. 2020; Muscarella et al. 2014).

The best model from these was selected based on statistical significance (partial ROC tests), performance (omission rate) and the Akaike information criterion. The settings of the best model were then used to run 30 bootstrap replicates, with no clamping or extrapolation while retaining a random partition of 30% of the points from each run. From these final models, the “cloglog” output format was used to assess median values across replicates as modelled distribution of cocoyam in Zimbabwe.

The relative contribution of each variable to suitability of cocoyam was calculated from median estimates across replicates of percent contribution, permutation importance and jackknife analysis. The most limiting variables were determined using the limiting factor approach in the “rmaxent” package (Baumgartner et al. 2017). This function identifies which bioclimatic variables weigh most negatively on the predicted suitability for each raster cell. The sensitivity–specificity equality approach which minimizes the absolute value of the difference between sensitivity and specificity was used to select the threshold for determining suitable and unsuitable areas to calculate area. This method was selected because it seeks to achieve a balance of accuracy for areas modelled for presence and absence of the species and is the recommended approach for presence only suitability models where prevalence is usually low (Bean et al. 2012; Cantor et al. 1999; Hernandez et al. 2006).

2.5 Climate change impact assessment data

Replacing the current climate data with the projections and comparing the results shows the impact of climate change on crop suitability (Chapman et al. 2020; Jayasinghe and Kumar 2019; Ramirez-Cabral et al. 2016). This is based on the understanding that the determining crop-climatic relationships hold under future climatic conditions as no dramatic changes in these are expected (e.g. no future genotypes will half the growth period or the water requirement of the crop). To assess the impact of climate change on cocoyam potential, the current weather data were replaced by future projected climate data. Two future periods 2050 (average of 2040–2060) and 2070 (average of 2040–2060) were used in the study. Three different global climate models (GCMs) were used for future climate data and these were the Community Climate System Model (CCSM4) (Gent et al. 2011), Hadley Centre Climate Model Earth System Model (HadGEM) (Jones et al. 2011) and Model for Interdisciplinary Research on Climate-Earth System Model (MIROC5) (Watanabe et al. 2011) from CMIP5 data that were used. The GCMs were chosen because they are available with bias-adjustment and downscaled using quantile mapping to adjust target distributions as empirically estimated from source distribution in the form of cumulative distribution functions. These models are also widely used in climate change impact studies

in Africa because they feature as reliable for the region in model evaluation studies (Aloysius et al. 2016; Klutse et al. 2016; Ongoma et al. 2019).

All the four representative concentration pathways (RCPs), RCP2.6, RCP4.5, RCP6.0 and RCP8.5 which represent the possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6 and 8.5 W/m², respectively), were used as emission scenarios. The RCP2.6 represent the “very stringent” pathway requiring that that carbon dioxide (CO₂) emissions start declining by 2020 and go to zero by 2100. RCP4.5 is considered the intermediate scenario based on peak emissions around 2040, and then decline to half of those in 2050 by 2100. RCP6.0 emissions are projected to peak around 2080, and then decline, and RCP8.5 is based on emissions continuing to rise throughout the twenty-first century (Meinshausen et al. 2011; van Vuuren et al. 2011).

2.6 Evaluation of micro-climate regulation as an adaptation measure for cocoyam resilience

After the analysis of the variable importance and the response curves, we evaluated the potential of adjusting the canopy micro-climate conditions by adjusting the variables to mimic adaptation measures with special focus on modelling how agroforestry can be used for resilience building in cocoyam production in Zimbabwe. The potential of agroforestry to cushion crop production under climate change has already been elucidated in detail (Lasco et al. 2014; Reppin et al. 2019; Sanou et al. 2012). Among the key roles of agroforestry systems for crops are regulating the temperature and moisture regimes of understory crops and this has direct influence on variation in temperature as represented by the temperature seasonality variable.

Studies have indicated that agroforestry reduces temperatures of understory crops by 0.14 °C for every percent increase in tree canopy cover (Middel et al. 2015). While this is important under a warming climate, perhaps the greatest benefit of agroforestry is the cushion against climatic extremes in which trees buffer temperature and atmospheric saturation deficit, thereby effectively reducing exposure to supra-optimal temperatures that reduce or stop physiological and developmental processes and resultant yield outcomes of crops (Chemura et al. 2020b; Mbow et al. 2014; van Noordwijk et al. 2014). We therefore hypothesized that, depending with the various levels of shading, the temperature amplitudes of cocoyam will be regulated by agroforestry and sought to understand how this will impact on suitability of cocoyam under the different scenarios and periods (Ong and Kho 2015; Sida et al. 2018).

Temperature seasonality is the amount of temperature variation over a given year based on the standard deviation of monthly temperature averages (O'Donnell and Ignizio 2012). Agroforestry systems reduce this variation by various magnitudes depending on tree species and intensities. In addition, agroforestry controls water retention mainly mediated through soil temperature, blocked radiation and overall reduced atmospheric evaporative demand (Chemura et al. 2020b). To provide agroforestry model evaluation that is agnostic to tree species, we used percentage changes in this variable which can be achieved by diverse setups of systems and through various tree species or tree mixes in cocoyam production systems. To implement this, the temperature and precipitation seasonality variables were adjusted by reducing these by 5%, 10% and 15% and running the suitability models with all the other variables remaining constant. The opportunities for this evaluation of agroforestry under climate change in this way were first suggested and discussed in detail by Luedeling et al. (2014), but implementation as in our study remained elusive.

The effects of the adaptation measure were measured as the difference between the performance of the adaptation measure under current conditions and that under projected climate conditions after Lobell (2014). We adopted this approach because many impact studies consider adaptation as the difference between with and without intervention under future climate conditions, which overestimates/exaggerates the benefit of a measure. The actual adaptation effect of an intervention is therefore the difference between the suitability under future climate change and the suitability of the measure under current climatic conditions. In this way, we clearly distinguish between adaptation measures and agricultural intensification measures by elucidating only the climate change buffering potential of the measure.

3 Results

3.1 Model calibration and accuracy assessment

The assessment of the model fit showed that most of the linear model fit had zero weights, indicating low discriminatory abilities compared to other feature classes and combinations. Most of the climatic variables had quadratic and hinge fits to the training data for cocoyam. The best model had regularization multiplier (RM) of 1.5 and feature class of linear, quadratic, hinge and product (LQHP) (Supplementary Information 2). Evaluation of the model performance showed that the models for cocoyam performed very well with area under the receiver operating curve (AUC) of over 0.85 for all model parameter combinations in calibration. The final Maxent model for cocoyam had a training AUC of 0.93 and a test AUC of 0.91 (Supplementary Information 3). This model captured the suitability of the currently known production areas of cocoyam with only 3.4% of current sample points outside range and providing an additional visual confirmation of good model performance. This model performance provided sufficient confidence in the model for predicting the suitability of cocoyam under current and projected climatic conditions.

3.2 Factors affecting the distribution of cocoyam in Zimbabwe

Table 2 shows the percent contribution of the predictor variables in the prediction of agro-climatic suitability of cocoyam under current climatic conditions. The results showed that temperature-related factors (mean temperature of wettest quarter, temperature seasonality, mean annual temperature) were most important for cocoyam as these explained a total of about 53.8% of the suitability of cocoyam in the country, with the remainder explained by precipitation-related factors, soil and altitude (Table 2). The mean temperature of the wettest quarter was the most limiting factor for cocoyam, explaining 29.6% of the distribution in Zimbabwe, followed by seasonality of precipitation (23.9%). The importance of temperature seasonality (17.6%) and precipitation seasonality (23.9%) were substantial as an individual factors, indicating that both temperature and precipitation, especially their seasonality, are important for defining the range for the crop in the country.

The distribution of the most limiting factors for each location is shown in Fig. 2. The western parts are mostly limited by temperature seasonality (Bio4), while in the northern areas seasonality of precipitation (Bio15) is mostly limiting, explaining why these are considered by the model to be important variables (Table 2). As cocoyam is a long-season crop, it was not surprising that precipitation of the wettest quarter was not significant

Table 2 Percentage contribution of the predictor variables for cocoyam in Zimbabwe and the respective mean changes for each variable all sample point areas in Zimbabwe. The changes are mean changes of the 3 GCMs (detailed results for each GCM are in Supplementary Materials 4)

Variable	Bio1	Bio4	Bio8	Bio12	Bio15	Bio16	Altitude	Soil type
Variable importance	6.6	17.6	29.6	18.3	0.3	23.9	3.5	0.1
Current value	18.4	2811	20.9	936.7	97.2	578.8	1164.3	-
2050	RCP2.6	1.6	96.7	1.4	-23.8	7.8	16.8	-
	RCP4.5	1.9	86.4	1.7	-7.4	7	27.5	-
	RCP6.0	1.8	57.6	1.5	5.7	8.1	35.7	-
	RCP8.5	2.5	99	2.3	-4.1	9.1	36.6	-
2070	RCP2.6	1.6	134.5	1.5	-26.3	9.7	25.5	-
	RCP4.5	2.3	118.8	2.1	-17.2	8.5	39.1	-
	RCP6.0	2.4	113.4	2.3	16.2	8.3	49.8	-
	RCP8.5	3.7	168.6	3.5	-26.2	10.9	27.4	-

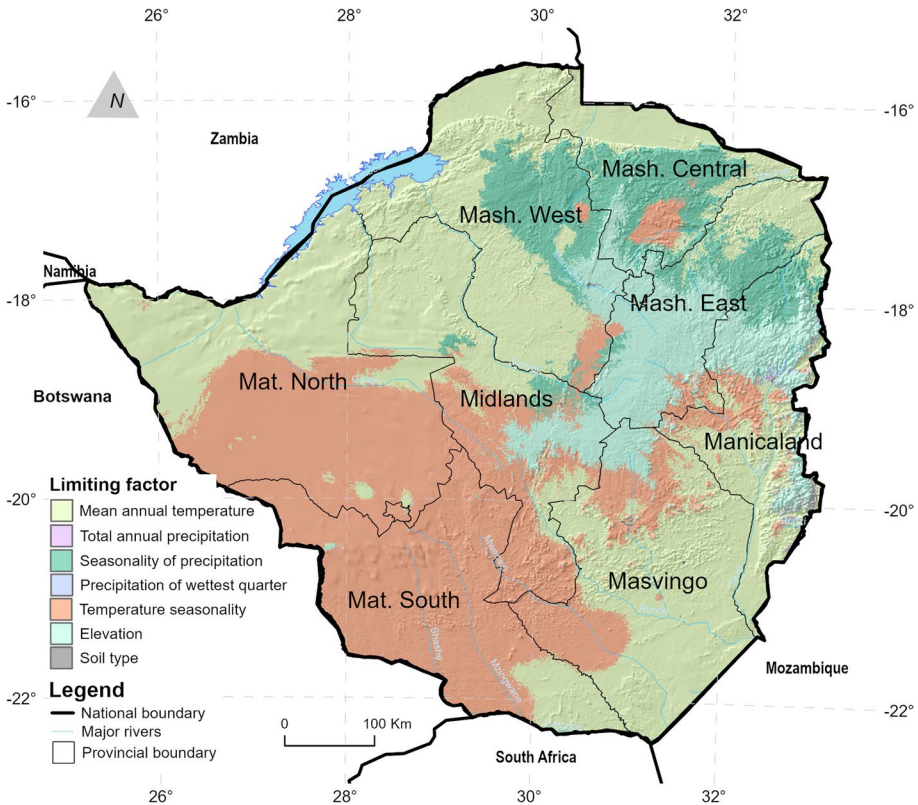


Fig. 2 Distribution of the limiting factors for cocoyam production in Zimbabwe. The map depicts which environmental factor in the Maxent models contributes most negatively to the suitability at each raster cell. The variables are mean annual temperature (Bio1), temperature seasonality (Bio4), mean temperature of wettest quarter (Bio8), total annual precipitation (Bio12), seasonality of precipitation (Bio15), precipitation of wettest quarter (Bio16), elevation and soil type

(0.3%). Further analysis of the response curves showed that cocoyam preferred areas with less variable rainfall in the year together with cooler temperature during the period of maximum rainfalls (Supplementary Information 4). The fact that elevation was considered not important was not expected as current production areas are mainly the eastern highlands of the country. Our results show therefore that it is more the climate variables than the geo-physical parameters that are important for the crop, as it can be produced elsewhere where climatic conditions are met.

3.3 Current and projected suitability of cocoyam

Under current climate conditions, the model shows that cocoyam is suitable mostly in five districts in eastern Zimbabwe. These are Chimanimani, Chipinge, Makoni, Mutasa and Nyanga with parts of Marondera, Murehwa and Wedza. The highest mean suitability for sample points are for Chipinge followed by Mutasa where the probabilities are above 0.8 (Fig. 3). In terms of land area, at national level, just 4.3% of the country is suitable for cocoyam, representing 10.6% of all agricultural land in the country under current climatic conditions. District level proportions suitable for the crop are highest for Mutasa with 66.7% followed by Chimanimani with 65.8%. These do not follow the probabilities which are highest for Chip9inge and Mutasa. The model identified parts of Bikita (10.1%), Zaka

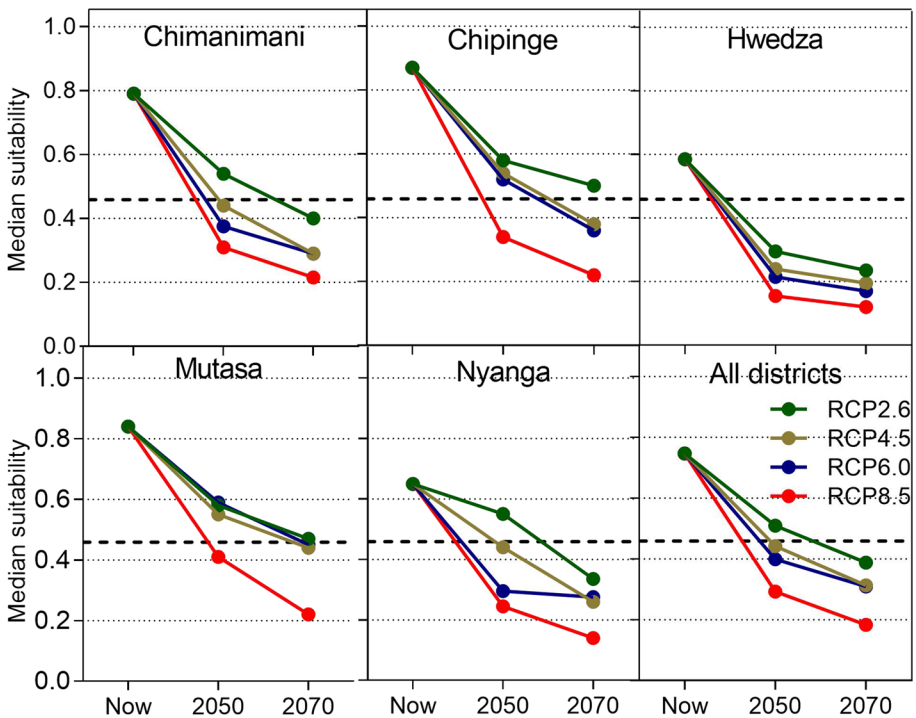


Fig. 3 Changes in cocoyam suitability in sampling points in major cocoyam producing districts in Zimbabwe. The values of each sampling point was extracted and district averages calculated to determines the changes by 2050 and 2070 under current, RCP2.6, RCP4.5, RCP6.0 and RCP8.5 climatic conditions

(22.2%) and Masvingo (8.1) as suitable for cocoyam production and yet these areas are outside the current sample points (Fig. 4). Combined, these identified belts contribute over 10% of the area modelled as currently suitable for cocoyam production, indicating potential new areas for growing the crop under current conditions (Table 2).

3.4 Cocoyam suitability under climate change

The impacts of climate change on suitability on current production sites are variable depending on the district, the time and the emission scenario. Although decreases in suitability are projected for all districts, the results show that Chimanimani district will have the most significant range shift in suitability for cocoyam under all scenarios followed by Nyanga. Changes under the RCP8.5 are drastic for median suitability of cocoyam especially in Chipinge and Mutasa districts (Fig. 4). However, using the determined suitability threshold (0.46), cocoyam production will become untenable under RCP8.5 in all districts and under RCP4.5 and RCP6.0 and RCP8.5 only in Hwedza district.

Our results show a strong change of cocoyam mean suitability in Zimbabwe with respect to future climate change scenarios (Fig. 3). The most change in cocoyam mean suitability at current points is for Chimanimani and Hwedza districts. Compared to the current climate suitability map, in the year 2050, some of the suitable areas will become less suitable especially the northern suitable districts, depending on the RCP (Fig. 4a–e). It is evident that suitability for cocoyam will narrow in Marondera, Makoni and Nyanga districts with suitability losses of around a quarter of the area currently suitable under RCP8.5 by 2050 and almost all suitable areas diminished by 2070 under the same scenario (Table 2, Fig. 5). On the other hand, the model results show that in Chipinge, suitability will increase by 2050 under RCP2.6 (0.5%) but suitability decreases are expected under other scenarios. There are more severe losses in suitability by 2070 under all scenarios except in all districts (Fig. 5a–e). Chipinge district is projected as the most stable district for production of cocoyam across the two periods and four climatic scenarios.

Comparison of the 4 model projections shows that all the four models indicated similar patterns of impact of climate change on cocoyam suitability in Zimbabwe (Fig. 6). However, the CCSM4 model predicts increases in suitability by 2050 and 2070 under the RCP2.6 scenario (Fig. 6), with the HADGEM and MIROC5 models indicating decreases in net suitability for the crop under all scenarios (Fig. 6, Supplementary Information 6).

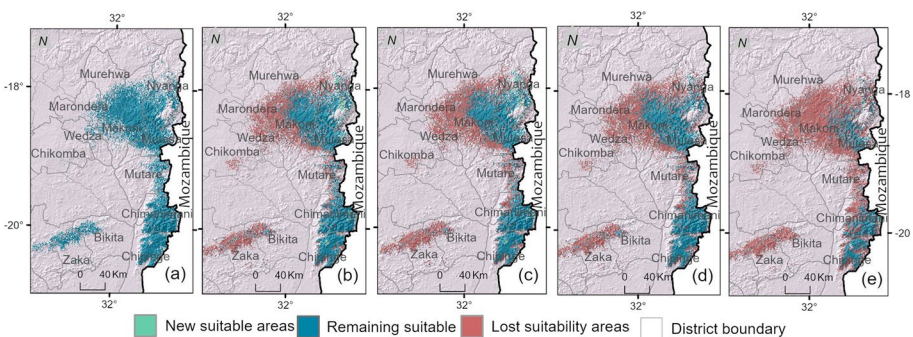


Fig. 4 Map showing the suitability and changes in suitability of cocoyam in Zimbabwe by 2050 under (a) current (b) RCP2.6, (c) RCP4.5, (d) RCP6.0 and (e) RCP8.5 climatic conditions

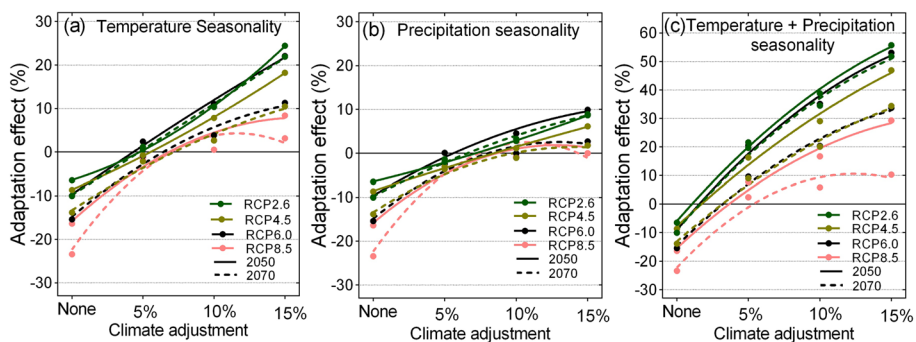


Fig. 7 Modelled effect of adjusting seasonality of temperature on cocoyam suitability under different scenarios for 2050 and 2070

temperature adjustment (Fig. 7b), despite it having a higher percentage contribution than the former. The highest adaptation effect was obtained from the interaction of both temperature and precipitation (Fig. 7c). Overall, the highest adaptation effect is under RCP2.6 and the least under RCP8.5 for both 2050 and 2070. There is more adaptation effect for the year 2050 (Fig. 7a) for all scenarios compared to 2070. Results show that in all cases, cocoyam suitability was higher than when no adaptation measure is implemented, indicating potential for buffering climate change impacts on suitability.

4 Discussion

In this study, we applied a suitability model to estimate and understand the impacts of climate change on cocoyam in Zimbabwe under different emission scenarios for 2050 and 2070. In this study, we identified high potential areas for cocoyam in which production of the crop can be enhanced for food security and livelihoods. We also identified the areas that will be mostly affected by changing climate and therefore provide an impetus for development of adaptation measures for the crop in change hotspots. Overall, the study provides a quantitative assessment of climate impacts on cocoyam, one of the underutilized and neglected crops.

This analysis showed that cocoyam requires very specific environmental and edaphic factors, which are found in specific areas of the country. The finding that cocoyam is more influenced by temperature factors corroborates the assertion that it is a temperature sensitive crop (Taylor et al. 2019). This also explains why cocoyam is also commonly produced under shade trees (Oke et al. 1990; Thiele et al. 2017) where the temperature regimes are regulated by the overhead canopy. Temperature of the wettest quarter represents an interaction of temperature and precipitation and is related to crop water use and evaporative losses. The wettest quarter (January–March) is the period of peak development of the crop and occurs months after planting which normally occurs in the 3rd quarter (July–September).

The annual sum and the distribution of the precipitation were also among the most important factors that are explainable by the fact that cocoyam is a long-season crop that, unlike annual cereals and legumes, requires a sufficient supply of water for the greater part of the year. As such water management has been found as one of the most important factors in yield of cocoyam (Lim 2015; Mabhaudhi et al. 2013). Similar

importance of precipitation factors have been reported for other perennial crops such as coffee (Chemura et al. 2016) and tea (Jayasinghe and Kumar 2019). The potential for production of cocoyam in Zimbabwe is variable as determined by the distribution of the factors that affect production. The identified suitable areas correspond with current production areas. This confirms that farmers are rational and grow crops in the areas in which they are most suited, although markets, culinary preferences, experience with the crop and other policies may also influence farmers' crop choices outside most suitable areas.

The district level assessment shows that there is a spatially disproportionate response of cocoyam production to climate change in Zimbabwe as some districts are at higher risk compared to others. Our results indicate generally that cocoyam is unlikely to get extinct in current production areas in Zimbabwe under climate change (except under RCP8.5) at least until 2070 but it will become more difficult to achieve current production levels. In addition, the production areas that are currently marginal will be most affected by climate change, making cocoyam production more difficult or impossible without adaptation measures in these areas. The shrinking potential areas for production of cocoyam pose severe threats to the growth of the production of the bio-culturally important crop as current potential expansion areas will diminish in the future. The higher climatic risk in potential but currently uncultivated areas is not surprising as similar trends have been observed in similar modelling studies elsewhere (Jayasinghe and Kumar 2019; Kodis et al. 2018).

There are implications of decreases in cocoyam potential under climate change to farmers, communities and consumers of cocoyam in Zimbabwe. Firstly, the losses in suitability imply the combined losses in potential for obtaining not just corms, but extend to benefits of leaves, petioles and flowers, which are frequently consumed as a vegetable representing an important source of vitamins and iron (Singh et al. 2012; Taylor et al. 2019). Compared with other agricultural crops that only produce one source of food, this indicates that there is potentially more loss in not just a food source but an important source of micro-nutrients and income from other consumed parts of the crop. Secondly, the fact that cocoyam is produced in high intensity (Darkwa and Darkwa 2013; Deo et al. 2009) in seemingly marginal lands that are not suitable for traditional crops such as maize and sorghum (Matthews 2010; Temesgen and Retta 2015; Tumuhimbe 2015; Ubalua et al. 2016) means that migrating from cocoyam to other crops entails more land, labour and input requirements, which are already limited for many smallholder farmers (Heumann et al. 2011). Thirdly, and perhaps most importantly, the harvesting and consumption of cocoyam in Zimbabwe extend to the lean period in which other common food crops are not available and the decreases in its suitability increase risks of food insecurity.

In addition, cocoyam has very high productivity potential in a small area (up to 120 MT/ha) and a higher market value than less productive and less yielding crops (Lim 2015; Mabhaudhi et al. 2013; Onyeka 2014; Shiyam et al. 2007). Achieving similar land equivalent ratios with other crops will mean opening up new areas which is not sustainable in the long term. Cocoyam is also a high-value crop fetching higher market prices than common legumes and cereals, meaning that if farmers are to migrate to other crops, they lose this potential income stream per unit of land by moving to lower value crops (Onyeka 2014). Furthermore, cocoyam provides complementary nutrients that are important in providing balanced diets. For examples, its crude protein content is higher than that of other tubers (Stone et al. 2011; Valenzuela and Defrank 1995) and it is richer in essential minerals (Ca, Mg and P) than other tuber crops and is highly recommended for diabetic patients, the aged, children with allergies and for persons with intestinal disorders (Onyeka 2014; Prajapati et al. 2011; Rees et al. 2012; Thiele et al. 2017).

Proper design and implementation of adaption measures could maintain cocoyam production in almost all the districts that are producing the crop currently, given that the decreases in suitability are not drastic except for RCP8.5 scenario by 2070. We find that there is potential in production of cocoyam in agroforestry systems or forestry understorey systems as the crop is tolerant to shaded conditions, as suggested by our results on effect of microclimatic regulation (Lim 2015; Sanou et al. 2012). Such potential is especially important in that trees have been decreasing in many farmlands and yet have complementary roles in carbon sequestration, nutrient cycling and climate regulation (Carreño-Rocabado et al. 2019; Daniel and Carlos 2016; Miller et al. 2017). The ability of cocoyam to be productive under agroforestry is based on its ability to accumulate photosynthates under shaded conditions, making it among the most prolific terrestrial crops in shaded metabolism (Valenzuela and Defrank 1995).

In addition, there is a need to identify the best-bet practices in cocoyam production and use them to train trainers in extension staff. In addition, there is need for capacity building of farmers in cocoyam production by including and mainstreaming it in extension packages for areas in which it can be produced. Water conservation and management systems particularly irrigation are also another potential climate change adaptation measure for cocoyam, given that the projections indicate increases in temperature and decreases in rainfall total and distributions. The selection of drought tolerant cocoyam varieties is important to build resilience especially for loss districts such as Makoni, Hwedza and Mutasa. According to Ganança et al. (2015) and Mabhaudhi et al. (2013), the response of different cocoyam cultivars to drought is variable and therefore choice of appropriate cultivars is important for production under climate change. There is need for the drought tolerant varieties to have comparable preparatory qualities such as starch granule sizes, amylose content, viscosity, pasting time, water absorption capacity, gelling point, foam capacity, bulk density and swelling power (Falade and Okafor 2013; Isibhakhomen et al. 2013; Kaushal et al. 2012) and nutritional qualities such as protein, energy, calcium, potassium and other micronutrients (Akwee et al. 2015; Darkwa and Darkwa 2013). The changes in production and preparatory characteristics are of special interest given the gender bias of neglected and underutilized crops such as cocoyam that are almost entirely a preserve of women.

Although the results of this study are robust and reliable (given the high AUC values), there are a number of issues that should be considered in interpretation and application of results. In modelling distributions in human-managed ecosystems, the definition of the range should be according to social factors such as cultural preference and tradition, which are so difficult to represent in quantitative models and yet may have an influence on the observations of presence points used for running the model. Suitability does not directly translate to production potential as many factors may affect the farmers' decisions to produce or not to produce the crop. As explained in the model assumptions, these socioeconomic factors (including availability of markets, experience, availability of extension support, culture among others) are difficult to capture in this type of modelling and should be considered in application of model results.

In addition, the effect of CO₂ fertilization on cocoyam is not captured for each of the RCPs used and yet this may have a positive impact on photosynthesis (and growth) for C3 plants like cocoyam (McGrath and Lobell 2013; Reich and Hobbie 2013). The implication of this omission is that we may have over-estimated the decrease in suitability and underestimated the increased suitability in our study by not capturing the positive effects of CO₂ fertilization. However, the response of crop plants to CO₂ fertilization is strongly dependent on plant water relations and soil nutrients (Taub 2010; Wang et al. 2020), and yet it is established that impacts of climate change on water availability will be severe (Kusangaya

et al. 2014; Pohl et al. 2017) while nutrient supply is low on already depleted soils in many areas in Africa (Nalivata et al. 2017). The net effect of this is that there is uncertainty about the potential impact of CO₂ fertilization on changes in suitability of cocoyam with further modelling and field studies required.

5 Conclusion

This research aimed to demonstrate the potential application of an approach for assessing suitability of culturally important, but largely neglected orphan crops, such as cocoyam. The implementation of the suitability model allowed the most suitable areas for cropping cocoyam in Zimbabwe to be identified and these should be included in the extension and agricultural policy. Running the model with different climate change scenarios showed that there will be a decrease in potential for cocoyam production in Zimbabwe under all climate change scenarios. The impacts of climate change on cocoyam suitability are variable depending on the districts and the climate scenarios. We conclude that a suitability model can provide spatially explicit information about the current and future suitability of cultivated crops such as cocoyam and provide insights that can be used for planning and building resilience. We recommend that agroforestry, which positively changes the temperature on a micro scale, is an effective climate change adaptation strategy to maintain cocoyam production under climate change.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11027-022-10014-9>.

Acknowledgements We are grateful to the Agricultural Technical and Extension department (AGRITEX) in Zimbabwe for providing the production data that was used in the modelling study.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability All used data is available in the manuscript and in supplementary materials. Original files are available from author on reasonable request.

Code availability Code will be stored on Github of corresponding author.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Akwee P, Netondo G and Palapala VA (2015) A critical review of the role of taro *Colocasia esculenta* L.(Schott) to food security: a comparative analysis of Kenya and Pacific Island taro germplasm
- Aloysius NR, Sheffield J, Saiers JE, Li H, Wood EF (2016) Evaluation of historical and future simulations of precipitation and temperature in central Africa from CMIP5 climate models. *J Geophys Res: Atmos* 121(1):130–152
- Anderson RP, Gonzalez I Jr (2011) Species-specific tuning increases robustness to sampling bias in models of species distributions: an implementation with Maxent. *Ecol Model* 222(15):2796–2811. <https://doi.org/10.1016/j.ecolmodel.2011.04.011>
- Austin M (2007) Species distribution models and ecological theory: a critical assessment and some possible new approaches. *Ecol Model* 200(1–2):1–19
- Baumgartner J, Wilson P and Esperón-Rodríguez M (2017) Rmaxent: tools for working with Maxent in R. R package version 0.8.3.9000
- Bean WT, Stafford R, Brashares JS (2012) The effects of small sample size and sample bias on threshold selection and accuracy assessment of species distribution models. *Ecography* 35(3):250–258
- Beck J (2013) Predicting climate change effects on agriculture from ecological niche modeling: who profits, who loses? *Clim Change* 116(2):177–189
- Cantor SB, Sun CC, Tortolero-Luna G, Richards-Kortum R, Follen M (1999) A comparison of C/B ratios from studies using receiver operating characteristic curve analysis. *J Clin Epidemiol* 52(9):885–892
- Carreño-Rocabado G, Amores F, Ordoñez J, Cerda R and Somarriba E (2019) Trees on farms products and species diversity in two municipalities of Nicaragua-Honduras Sentinel Landscape. Retrieved from <https://data.worldagroforestry.org/dataset.xhtml?persistentId=,> <https://doi.org/10.34725/DVN/LO7G0A>
- Chapman S, Birch CE, Pope E, Sallu S, Bradshaw C, Davie J, Marsham JH (2020) Impact of climate change on crop suitability in sub-Saharan Africa in parameterized and convection-permitting regional climate models. *Environ Res Lett* 15(9):094086
- Chemura A, Kutuywayo D, Chidoko P, Mahoya C (2016) Bioclimatic modelling of current and projected climatic suitability of coffee (*Coffea arabica*) production in Zimbabwe. *Reg Environ Change* 16(2):473–485
- Chemura A, Schaubberger B, Gornott C (2020a) Impacts of climate change on agro-climatic suitability of major food crops in Ghana. *PLoS ONE* 15(6):e0229881
- Chemura A, Yalaw AW and Gornott C (2020b) Quantifying agroforestry yield buffering potential under climate change in the smallholder maize farming systems of Ethiopia. *Front Agro*
- Cuervo P, Percara A, Monje L, Beldomenico P and Quiroga M (2020) Environmental variables determining the distribution of an avian parasite: the case of the *Philornis torquans* complex in South America. *Med Veterinary Entomol*
- Daniel C and Carlos J (2016) Prevalence, economic contribution, and determinants of trees on farms across Sub-Saharan Africa. *Forest Policy Econ*
- Darkwa S, Darkwa A (2013) Taro (*Colocasia esculenta*): it's utilization in food products in Ghana. *J Food Process Technol* 4(5):1–7
- Deo PC, Tyagi AP, Taylor M, Becker DK, Harding RM (2009) Improving taro (*Colocasia esculenta* var *esculenta*) production using biotechnological approaches. *South Pacific J Nat Appl Sci* 27(1):6–13
- Dhliwayo P (2002) Underexploited tuber crops in Zimbabwe: a study on the production of Livingstone potato (*Plectranthus exculentus*). *PI Genet Resource Newsl* 130:77–80
- Elith J, Phillips SJ, Hastie T, Dudík M, Chee YE, Yates CJ (2011) A statistical explanation of MaxEnt for ecologists. *Divers Distrib* 17(1):43–57
- Eneh OC (2013) Towards food security and improved nutrition in Nigeria: taro (*Colocasia antiquorum*) grit as carbohydrate supplement in energy food drink. *African J Food Sci* 7(10):355–360
- Estes L, Bradley B, Beukes H, Hole D, Lau M, Oppenheimer M, Turner W (2013) Comparing mechanistic and empirical model projections of crop suitability and productivity: implications for ecological forecasting. *Glob Ecol Biogeogr* 22(8):1007–1018
- Evangelista P, Young N, Burnett J (2013) How will climate change spatially affect agriculture production in Ethiopia? Case studies of important cereal crops. *Clim Change* 119(3–4):855–873
- Falade KO, Okafor CA (2013) Physicochemical properties of five cocoyam (*Colocasia esculenta* and *Xanthosoma sagittifolium*) starches. *Food Hydrocolloids* 30(1):173–181
- FAO (1994) Definition and classification of commodities: roots and tubers and derived products. Food and Agriculture Organisation, Rome
- FAOSTAT (2016) Food and Agriculture Organization of the United Nations Statistics Division. Production Available in: <http://faostat3.fao.org/browse/Q/QC/S> Review date: April 2016

- Ganança JFT, Freitas JGF, Nóbrega HGM, Rodrigues V, Antunes G, Rodrigues M, Lebot V (2015) Screening of elite and local taro (*Colocasia esculenta*) cultivars for drought tolerance. *Procedia Environ Sci* 29:41–42
- Gent PR, Danabasoglu G, Donner LJ, Holland MM, Hunke EC, Jayne SR, Vertenstein M (2011) The Community Climate System Model version 4. *J Clim* 24(19):4973–4991
- Gödecke T, Stein AJ, Qaim M (2018) The global burden of chronic and hidden hunger: Trends and determinants. *Glob Food Sec* 17:21–29
- Hernandez PA, Graham CH, Master LL, Albert DL (2006) The effect of sample size and species characteristics on performance of different species distribution modeling methods. *Ecography* 29(5):773–785
- Heumann BW, Walsh SJ, McDaniel PM (2011) Assessing the application of a geographic presence-only model for land suitability mapping. *Eco Inform* 6(5):257–269
- Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *Int J Climatol: A J Royal Meteorol Society* 25(15):1965–1978
- Holzämper A, Calanca P, Fuhrer J (2013) Identifying climatic limitations to grain maize yield potentials using a suitability evaluation approach. *Agric for Meteorol* 168:149–159
- Isibhakhomen ES, Adeoti OV, Taiwo OO, Oluremi FE (2013) Extending the use of an underutilised tuber I: physicochemical and pasting properties of cocoyam (*Xanthosoma sagittifolium*) flour and its suitability for making biscuits. *African J Food Sci* 7(9):264–273
- Jarvis A, Ramirez-Villegas J, Campo BVH, Navarro-Racines C (2012) Is cassava the answer to African climate change adaptation? *Tropical Plant Biology* 5(1):9–29
- Jayasinghe SL, Kumar L (2019) Modeling the climate suitability of tea [*Camellia sinensis* (L.) O. Kuntze] in Sri Lanka in response to current and future climate change scenarios. *Agric for Meteorol* 272:102–117
- Jones C, Hughes J, Bellouin N, Hardiman S, Jones G, Knight J, Bell C (2011) The HadGEM2-ES implementation of CMIP5 centennial simulations. *Geosci Model Dev* 4(3):543–570
- Kaushal P, Kumar V, Sharma H (2012) Comparative study of physicochemical, functional, antinutritional and pasting properties of taro (*Colocasia esculenta*), rice (*Oryza sativa*) flour, pigeonpea (*Cajanus cajan*) flour and their blends. *LWT-Food Sci Technol* 48(1):59–68
- Kaushal P, Kumar V, Sharma H (2015) Utilization of taro (*Colocasia esculenta*): a review. *J Food Sci Technol* 52(1):27–40
- Klutze NAB, Abiodun BJ, Hewitson BC, Gutowski WJ, Tadross MA (2016) Evaluation of two GCMs in simulating rainfall inter-annual variability over Southern Africa. *Theoret Appl Climatol* 123(3):415–436. <https://doi.org/10.1007/s00704-014-1356-z>
- Kodis Mo, Galante P, Sterling EJ, Blair ME (2018) Ecological niche modeling for a cultivated plant species: a case study on taro (*Colocasia esculenta*) in Hawaii. *Ecol Appl* 28(4):967–977
- Kusangaya S, Warburton ML, Van Garderen EA, Jewitt GP (2014) Impacts of climate change on water resources in southern Africa: a review. *Phys Chem Earth, Parts a/b/c* 67:47–54
- Lasco RD, Delfino RJP, Espaldon MLO (2014) Agroforestry systems: helping smallholders adapt to climate risks while mitigating climate change. *Wiley Interdisciplinary Rev: Climate Change* 5(6):825–833
- Lim T (2015) *Colocasia esculenta*. In *Edible medicinal and non medicinal plants*. Springer. 454–492
- Lobell DB (2014) Climate change adaptation in crop production: beware of illusions. *Glob Food Sec* 3(2):72–76
- Luedeling E, Kindt R, Huth NI, Koenig K (2014) Agroforestry systems in a changing climate—challenges in projecting future performance. *Current Opinion in Environ Sustain* 6:1–7
- Mabhaudhi T, Modi A, Belete Y (2013) Response of taro (*Colocasia esculenta* L. Schott) landraces to varying water regimes under a rainshelter. *Agric Water Manage* 121:102–112
- Mabhaudhi T, Chimonyo VGP, Hlahla S, Massawe F, Mayes S, Nhamo L and Modi AT (2019) Prospects of orphan crops in climate change. *Planta* 1–14
- Matthews PJ (2010) An introduction to the history of taro as a food. *The Global Diversity of Taro* 6
- Mbow C, Van Noordwijk M, Luedeling E, Neufeldt H, Minang PA, Kowero G (2014) Agroforestry solutions to address food security and climate change challenges in Africa. *Current Opinion Environ Sustain* 6:61–67
- McGrath JM, Lobell DB (2013) Regional disparities in the CO₂ fertilization effect and implications for crop yields. *Environ Res Lett* 8(1):014054
- Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma ML, Lamarque J-F, Riahi K (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Clim Change* 109(1):213–241
- Middel A, Chhetri N, Quay R (2015) Urban forestry and cool roofs: assessment of heat mitigation strategies in Phoenix residential neighborhoods. *Urban Forestry & Urban Greening* 14(1):178–186
- Miller DC, Muñoz-Mora JC, Christiaensen L (2017) Prevalence, economic contribution, and determinants of trees on farms across Sub-Saharan Africa. *Forest Policy Econ* 84:47–61

- Müller C, Elliott J, Levermann A (2014) Food security: Fertilizing hidden hunger. *Nat Clim Chang* 4(7):540–541
- Muscarella R, Galante PJ, Soley-Guardia M, Boria RA, Kass JM, Uriarte M, Anderson RP (2014) ENM eval: An R package for conducting spatially independent evaluations and estimating optimal model complexity for Maxent ecological niche models. *Methods Ecol Evol* 5(11):1198–1205
- Mwenye OJ (2009) Genetic diversity analysis and nutritional assessment of cocoyam genotypes in Malawi. University of the Free State. 209
- Myers SS, Smith MR, Guth S, Golden CD, Vaitla B, Mueller ND, Huybers P (2017) Climate change and global food systems: potential impacts on food security and undernutrition. *Annu Rev Public Health* 38:259–277
- Nabout JC, Caetano JM, Ferreira RB, Teixeira IR, Alves SDF (2012) Using correlative, mechanistic and hybrid niche models to predict the productivity and impact of global climate change on maize crop in Brazil. *Natureza & Conservacao* 10:177–183
- Nalivata P, Kibunja C, Mutegi J, Tetteh F, Tarfa B, Dicko MK, Bayu W (2017) Integrated soil fertility management in Sub-Saharan Africa. Fertilizer use optimization in sub-Saharan Africa. 113–124
- Nyamapfene KW (1991) The soils of Zimbabwe (Vol. 1): Nehanda Publishers
- O'Donnell MS and Ignizio DA (2012) Bioclimatic predictors for supporting ecological applications in the conterminous United States. US Geological Survey Data Series. 691(10)
- Oke O, Redhead J, Hussain M (1990) Roots, tubers, plantains and bananas in human nutrition. *FAO Food Nutr Ser* 24:182
- Ong C and Kho R (2015) A framework for quantifying the various effects of tree-crop interactions. *Tree-Crop Interactions: Agroforestry in a Changing Climate*. CABI 1–23
- Ongoma V, Chen H, Gao C (2019) Evaluation of CMIP5 twentieth century rainfall simulation over the equatorial East Africa. *Theoret Appl Climatol* 135(3):893–910. <https://doi.org/10.1007/s00704-018-2392-x>
- Onyeka J (2014) Status of cocoyam (*Colocasia esculenta* and *Xanthosoma* spp) in West and Central Africa: production, household importance and the threat from leaf Blight. CGIAR Research Program on Roots, Tubers and Bananas (RTB)
- Opoku-Agyeman MO, Benneti-Lartey SO, Markwei C (2004) Agro-morphological and sensory characterization of cocoyam (*Xanthosoma sagittifolium* (L) (Schott) germplasm in Ghana. *Ghana J Agric Sci* 37(1):23–31
- Phillips SJ, Dudík M (2008) Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* 31(2):161–175
- Phillips SJ, Anderson RP, Schapire RE (2006) Maximum entropy modeling of species geographic distributions. *Ecol Model* 190(3–4):231–259
- Pohl B, Macron C, Monerie P-A (2017) Fewer rainy days and more extreme rainfall by the end of the century in Southern Africa. *Sci Rep* 7(1):1–7
- Prajapati R, Kalariya M, Umbarkar R, Parmar S, Sheth N (2011) *Colocasia esculenta*: a potent indigenous plant. *Int J Nutrition, Pharmacol Neurol Dis* 1(2):90
- Raemaekers RH (2001) Crop production in tropical Africa: DGIC Belgium
- Ramirez-Cabral NYZ, Kumar L, Taylor S (2016) Crop niche modeling projects major shifts in common bean growing areas. *Agric for Meteorol* 218:102–113
- Ray RC, Sivakumar PS (2009) Traditional and novel fermented foods and beverages from tropical root and tuber crops. *Int J Food Sci Tech* 44(6):1073–1087
- Rees D, Westby A, Tomlins K, Van Oirschot Q, Cheema M, Cornelius E, Amjad M (2012) Tropical root crops. *Crop Post-Harvest: Science and Technology, Perishables* 3:392
- Reich PB, Hobbie SE (2013) Decade-long soil nitrogen constraint on the CO₂ fertilization of plant biomass. *Nat Clim Chang* 3(3):278–282
- Reppin S, Kuyah S, de Neergaard A, Oelofse M and Rosenstock TS (2019) Contribution of agroforestry to climate change mitigation and livelihoods in Western Kenya. *Agroforestry Sys* 1–18
- Sanou J, Bayala J, Bazie P, Teklehaimanot Z (2012) Photosynthesis and biomass production by millet (*Pennisetum glaucum*) and taro (*Colocasia esculenta*) grown under baobab (*Adansonia digitata*) and néré (*Parkia biglobosa*) in an agroforestry parkland system of Burkina Faso (West Africa). *Exp Agric* 48(2):283–300
- Shiyam J, Obiefuna J, Ofoh M, Oko B, Uko A (2007) Growth and corm yield responses of upland cocoyam (*Xanthosoma sagittifolium* L) to saw dust mulch and NPK 20: 10: 10 fertilizer rates in the humid forest zone in Nigeria. *Cont J Agron* 1:5–10
- Sida TS, Baudron F, Kim H, Giller KE (2018) Climate-smart agroforestry: *Faidherbia albida* trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia. *Agric for Meteorol* 248:339–347

- Singh D, Jackson G, Hunter D, Fullerton R, Lebot V, Taylor M, Tyson J (2012) Taro leaf blight—a threat to food security. *Agriculture* 2(3):182–203
- Srinivasan R, Giannikas V, Kumar M, Guyot R, McFarlane D (2019) Modelling food sourcing decisions under climate change: a data-driven approach. *Comput Ind Eng* 128:911–919
- Stokland JN, Halvorsen R, Støa B (2011) Species distribution modelling—effect of design and sample size of pseudo-absence observations. *Ecol Model* 222(11):1800–1809
- Stone A, Massey A, Theobald M, Styslinger M, Kane D, Kandy D, Davert E (2011) Africa's indigenous crops. Retrieved from
- Taba-Morales G, Hyman G, Mejía JR, Castro-Llanos F, Beebe S, Rubyogo JC, Buruchara R (2020) Improving African bean productivity in a changing global environment. *Mitigation and Adaptation Strategies for Global Change* 1–17
- Tadele Z (2019) Orphan crops: Their importance and the urgency of improvement. *Planta* 1–18
- Taub D (2010) Effects of rising atmospheric concentrations of carbon dioxide on plants. *Nat Edu Knowledge* 1
- Taylor M, Lebot V, McGregor A and Redden RJ (2019) Sustainable production of roots and tuber crops for food security under climate change. *Food Sec Clim Change*
- Temesgen M and Retta N (2015) Nutritional potential, health and food security benefits of taro *Colocasia esculenta* (L.): a review. *Food Sci Qual Manag* 36
- Thiele G, Khan A, Heider B, Kroschel J, Harahagazwe D, Andrade M, Cherinet M (2017) Roots, tubers and bananas: planning and research for climate resilience. *Open Agriculture* 2(1):350–361
- Tumuhimbise R (2015) Plant spacing and planting depth effects on corm yield of taro (*Colocasia esculenta* (L) Schott). *J Crop Improve* 29(6):747–757
- Ubalua AO, Ewa F, Okeagu OD (2016) Potentials and challenges of sustainable taro (*Colocasia esculenta*) production in Nigeria. *J Appl Biol Biotechnol* 4(01):053–059
- Valenzuela HR, Defrank J (1995) Agroecology of tropical underground crops for small-scale agriculture. *Crit Rev Plant Sci* 14(3):213–238
- van Noordwijk M, Bayala J, Hairiah K, Lusiana B, Muthuri C, Khasanah NM and Mulia R (2014) Agroforestry solutions for buffering climate variability and adapting to change. *Climate Change Impact and Adaptation in Agricultural Systems*. Fuhrer J, Gregory PJ Eds. 216–232
- van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Rose SK (2011) The representative concentration pathways: an overview. *Clim Change* 109(1):5. <https://doi.org/10.1007/s10584-011-0148-z>
- Wang F, Gao J, Yong JW, Wang Q, Ma J, and He X (2020) Higher Atmospheric CO₂ Levels Favor C₃ Plants Over C₄ Plants in Utilizing Ammonium as a Nitrogen Source. *Front Plant Sci* 11
- Warren DL, Seifert SN (2011) Ecological niche modeling in Maxent: the importance of model complexity and the performance of model selection criteria. *Ecol Appl* 21(2):335–342
- Watanabe S, Hajima T, Sudo K, Nagashima T, Takemura T, Okajima H, Yokohata T (2011) MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments. *Geoscientific Model Development* 4(4):845
- Young N, Carter L and Evangelista P (2011) A MaxEnt model v3. 3.3 e tutorial (ArcGIS v10). Fort Collins, Colorado

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.