



Coffea arabica yields decline in Tanzania due to climate change: Global implications

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ABSTRACT

Coffee is the world's most valuable tropical export crop. Recent studies predict severe climate change impacts on *Coffea arabica* (*C. arabica*) production. However, quantitative production figures are necessary to provide coffee stakeholders and policy makers with evidence to justify immediate action. Using data from the northern Tanzanian highlands, we demonstrate for the first time that increasing night time (T_{\min}) temperature is the most significant climatic variable responsible for diminishing *C. arabica* yields between 1961 and 2012. Projecting this forward, every 1 °C rise in T_{\min} will result in annual yield losses of $137 \pm 16.87 \text{ kg ha}^{-1}$ ($P = 1.80\text{e-}10$). According to our ARIMA model, average coffee production will drop to $145 \pm 41 \text{ kg ha}^{-1}$ ($P = 8.45\text{e-}09$) by 2060. Consequently, without adequate adaptation strategies and/or substantial external inputs, coffee production will be severely reduced in the Tanzanian highlands in the near future. Attention should also be drawn to the arabica growing regions of Brazil, Colombia, Costa Rica, Ethiopia and Kenya, as substantiated time series evidence shows these areas have followed strikingly similar minimum temperature trends. This is the first study on coffee, globally, providing essential time series evidence that climate change has already had a negative impact on *C. arabica* yields.

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1. Introduction

Coffee is Tanzania's most important export crop, generating average export earnings in the order of 100 million USD per annum. The industry directly supports an estimated 2.4 million individuals in Tanzania (Tanzania Coffee Industry Development Strategy, 2012) and several millions more in similar agro-ecological conditions in neighboring Uganda, Kenya, Rwanda and Burundi. In accordance with other equatorial regions, warming has occurred over much of Tanzania, and most particularly since 1970 (IPCC, 2007; Williams and Funk, 2011). Recently, there has been increased attention on the substantial rise in night-time (minimum) temperatures and the effect these have on tropical crops, particularly in India and south-east Asia (e.g., Nagarajan et al., 2010; Bapuji Rao et al., 2014). In fact, on a global scale, minimum temperatures have increased about twice as fast as maximum temperatures (Vose et al., 2005; de los Milagros Skansi et al., 2013). Based on downscaled climate models, Tanzania is projected to experience a mean temperature increase of 2–4 °C by 2100 (IPCC, 2007; Agrawala et al., 2003; Läderach et al.,

2012). Using the Representative Concentration Pathway (RCP) 6.0 scenario (Meinshausen et al., 2011), future minimum temperature change will be most severe toward the interior regions of Tanzania, which is also where the major arabica growing regions are located (Fig. 1). Although progressive drying throughout the 20th century is well documented (e.g., Hulme et al., 2001; Mölg et al., 2006; Williams and Funk, 2011), uncertainty concerning rainfall projections for East Africa remains, which is exacerbated by atmospheric processes associated with altitudinal gradients (Pepin et al., 2010).

There have been significant research efforts predicting climate change and the effect it will have on coffee production systems in the tropics (e.g., Camargo, 2010; Davis et al., 2012; Jaramillo et al., 2013). However, there is still very little evidence that the observed changes and variability in climate patterns over recent decades have already impacted coffee production globally and particularly in East Africa. This is largely due to the fact that smallholder production systems in East Africa are data poor. To date, the anticipated impact of climate change on coffee production is predominantly based on studies that look at existing climate-coffee production gradients (e.g., Gay et al., 2006; Jaramillo et al., 2011; Jassogne et al., 2013), which then form the basis of suitability change maps based on downscaled Global Environmental Change (GEC) model projec-

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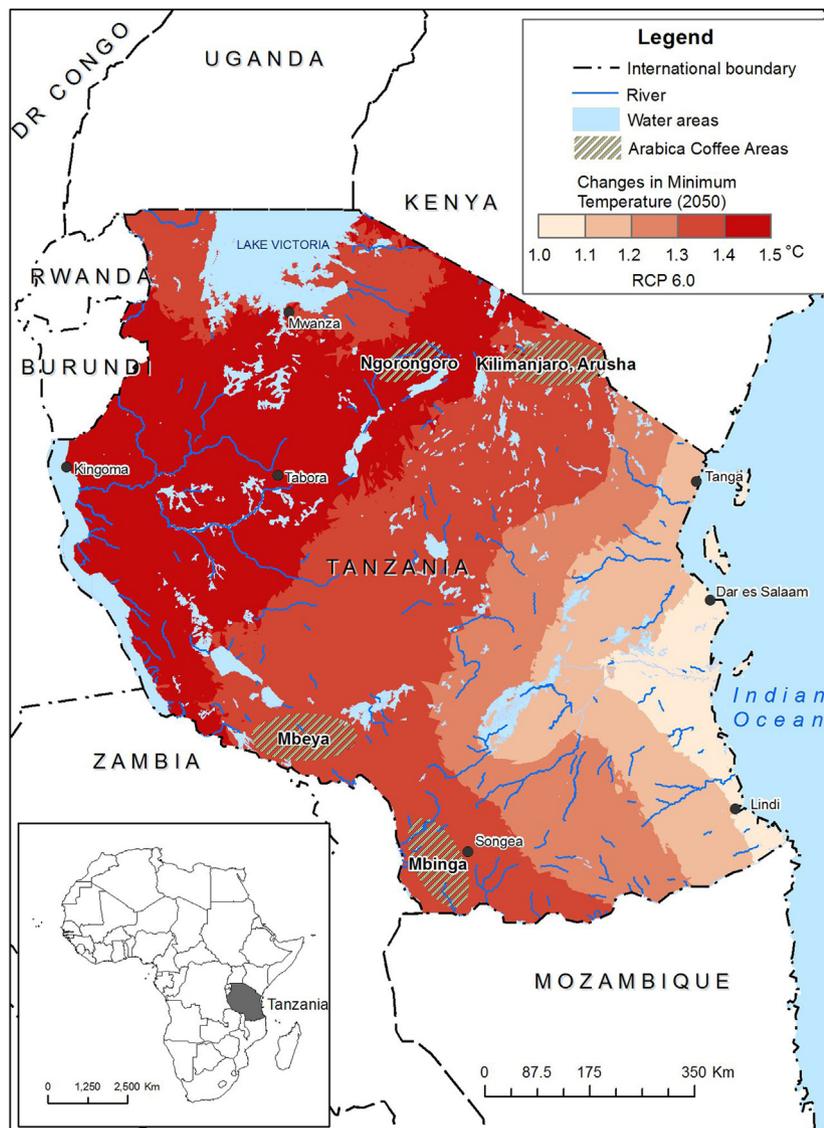


Fig. 1. Projected change in minimum temperatures for Tanzania to 2050. Future minimum temperature change is based on the Representative Concentration Pathway 6.0 (Meinshausen et al., 2011).

tions (e.g., Mwandosya et al., 1998; Davis et al., 2012; Läderach et al., 2012). In addition, several global change studies are based on interpolated climate data, such as the global gridded datasets from the Climate Research Unit (CRU) (<http://www.cru.uea.ac.uk/>). However, for some countries and regions, including the Tanzanian highlands, the number of stations used for interpolations is minimal. Concerns expressed by the scientific community do not always prompt action by coffee stakeholders and policy makers, as there is often a greater perceived need to address short term production and profitability challenges. However, the resource-constrained public and private sectors do not seem to invest seriously in climate change adaptation, as long as 'hard evidence' on immediate export losses (USD) and livelihood impacts are lacking.

The objective of our study is to quantify the impact of climate change on Tanzania's arabica coffee production. We aim to establish regional climate change trends for the northern highlands of Tanzania, and in so doing, identify the most significant atmospheric variables which have influenced coffee production in the region over the past 50 years (1960–2010). We quantify at which phenotypic phase this relationship is most important and use this model to make climate and yield projections to 2060. Further to this, we

review all other global *C. arabica* producing areas and highlight the regions which have followed similar climatic trends.

2. Materials and Methods

2.1. Study region and *C. arabica* yield data

In Tanzania, *C. arabica* is cultivated between ~1000 and 2300 m a.s.l along slopes of the northern Tanzanian highlands, including Mt. Kilimanjaro, Mt. Meru, and Tanga/Ngorongoro Crater highlands. Coffee is also cultivated in the southern highland regions of Mbeya and Mbeya, where the majority of small-holder arabica is grown. Shading, both natural and cultivated, is a common technique practised by the majority of small-holder farmers in Tanzania (Stigter, 1984). These systems create a unique microclimate, enabling the ability to modify the energy balance (Stigter, 1984), which may be of particular importance when considering Tanzania's future climate. Mt. Meru and Mt. Kilimanjaro boast high quality arabica and peaberry which retail for important price premiums. In addition, Tanzania benefits from a unique position in Japan as a direct result of the "Kilimanjaro" appellation (Tanzania Coffee Industry Development Strategy, 2012). Given that the

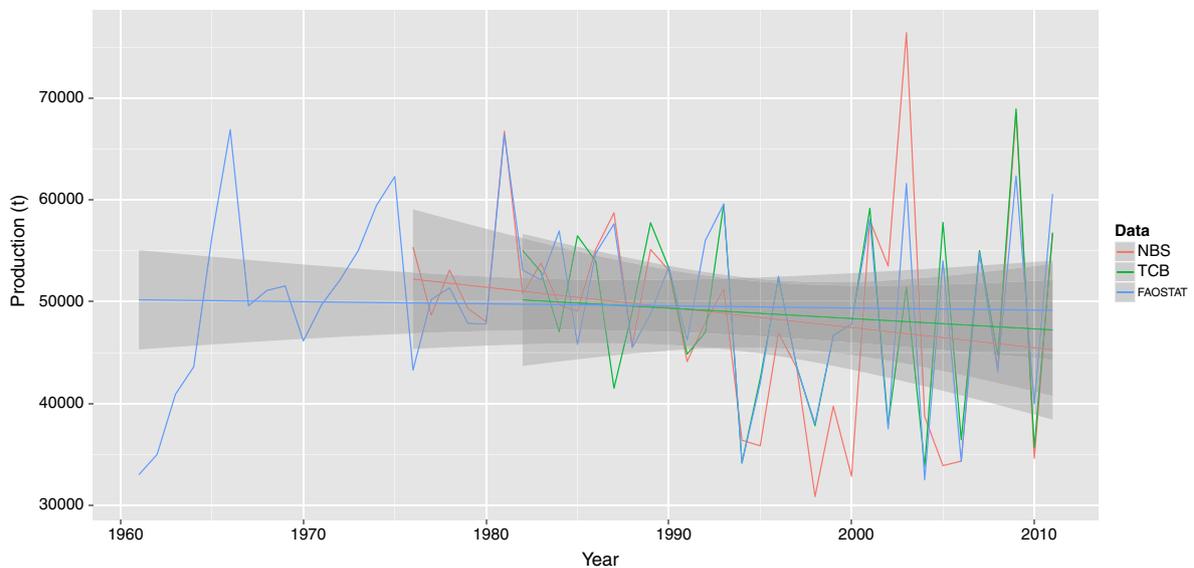


Fig. 2. Annual clean bean arabica production trends for Tanzania. Trends are for the period 1962–2012 (FAOSTAT), 1976–2012 (NBS) and 1976–2012 (TCB). A linear regression line with an associated confidence band of 95% is fitted to each series.

majority (>90%) of coffee in Tanzania is produced by smallholder farmers (Tanzania Coffee Industry Development Strategy, 2012), this complicates obtaining accurate yield figures owing to inaccurate calculations, adjusted figures for political or economic reasons, illegal trade to other countries/regions, or disinterest in data collection and/or management. In addition, areas under cultivation are also associated with uncertainty due to inaccurate measurements and/or estimation of smallholder plot sizes (typically these are 1–2 ha), which are also intercropped in a multilayer vegetation structure consisting of banana (different varieties of *Musa*), beans, maize and cassava (Stigter, 1984; Hemp, 2006). Consequently, yield and production data were obtained from three separate sources to minimize this bias and error. The data sources include the Tanzania Coffee Board (TCB) (<http://www.coffeeboard.or.tz>), the Tanzanian National Bureau of Statistics (NBS) (<http://www.nbs.go.tz/>) and the agricultural statistics division of the Food and Agricultural Organization of the United Nations (FAOSTAT) (<http://faostat3.fao.org/faostat-gateway/go/to/home/E>) (Fig. 2). The FAOSTAT dataset is the longest series (1962–2013), followed by the NBS dataset (1976–2013) and then the TCB series (1982–2013). The data used are annual yield (kg ha^{-1}) and production (t) data of clean green bean arabica for the entire country. FAOSTAT is the only source providing details of area under cultivation (ha) for arabica, from which kg ha^{-1} outputs for each dataset were calculated.

2.2. Regional climate and data

The *C. arabica* growing regions of Tanzania occupy a unique niche comprising a temperate–humid climate within the high montane forest (Agrawala et al., 2003). Whilst the northern regions have experienced a mean annual temperature of 21 °C over the past five decades, by contrast, the southern highlands have had a much cooler climate (17.3 °C) over the same period. Situated within the tropics, these areas experience a bimodal rainfall pattern, with the long rains from March to May and the short rains from October to December (Agrawala et al., 2003). Large-scale climatic events such as the El Niño–Southern Oscillation (ENSO), as well as variability in the Indian Ocean sea surface temperatures (SSTs) are predominantly responsible for changes in temperature and precipitation (Pepin et al., 2010; Williams and Funk, 2011). Long-term temperature (monthly) and precipitation (daily)

data were obtained from the Tanzanian Meteorological Agency (<http://www.meteo.go.tz/>) for the corresponding 49 year period. In order to preserve important local climatic heterogeneity, four stations representing the main arabica growing regions of Tanzania were used. These include Lyamungu, Arusha and Moshi in the northern highlands, along the slopes of Mt. Kilimanjaro and Mt. Meru, and Mbeya from the southern highlands. Based on previous research outputs and given the specific location and corresponding climate of Tanzania's arabica growing regions, several bioclimatic indices of the phenologically-important stages (Silva et al., 2004; Silva et al., 2004) were calculated and used in the analysis. The variables consist of the mean minimum (T_{\min}), maximum (T_{\max}) and mean (T_{mean}) temperatures for the crop year, which extends from October to September in Tanzania. The mean minimum ($T_{\min F}$), maximum ($T_{\max F}$) and mean ($T_{\text{mean F}}$) temperatures during flowering (October–February) and the mean minimum ($T_{\min R}$), maximum ($T_{\max R}$) and mean ($T_{\text{mean R}}$) temperatures during development/ripening (March–September) were also used. Precipitation variables included the total rainfall for the crop year (P_{yr}), the total rainfall during the flowering period (P_{F}), the total rainfall during the dry season (P_{dry}) prior to harvest (June–September) and the number of rain days during the short rain season (PD_{short}), the long rain season (PD_{long}) and the flowering period (PD_{F}). Due to the biennial nature of the crop, each precipitation variable was also considered at a lag of two years prior to the event. Precipitation anomalies and the standard deviation (SD) was calculated for P_{yr} and also used as a variable.

2.3. Statistical analysis

Pearson's correlation coefficient (r) was used to determine significant relationships between the climatic variables and yield, and to select variables for each model. Separate correlation matrices were computed to account for the different lengths of datasets, and list-wise deletion was used to ensure unbiased parameter estimates. All-subsets regression was used as a complementary data mining technique to select parameters for each model. Similar to regression subsets, it performs an exhaustive analysis of all possible variables and presents the best candidates for each subset size. Since the efficient branch-and-bound algorithm returns a best model of each size, the results do not depend on a penalty model for model size (Shmueli, 2010). Climatic periods and variables

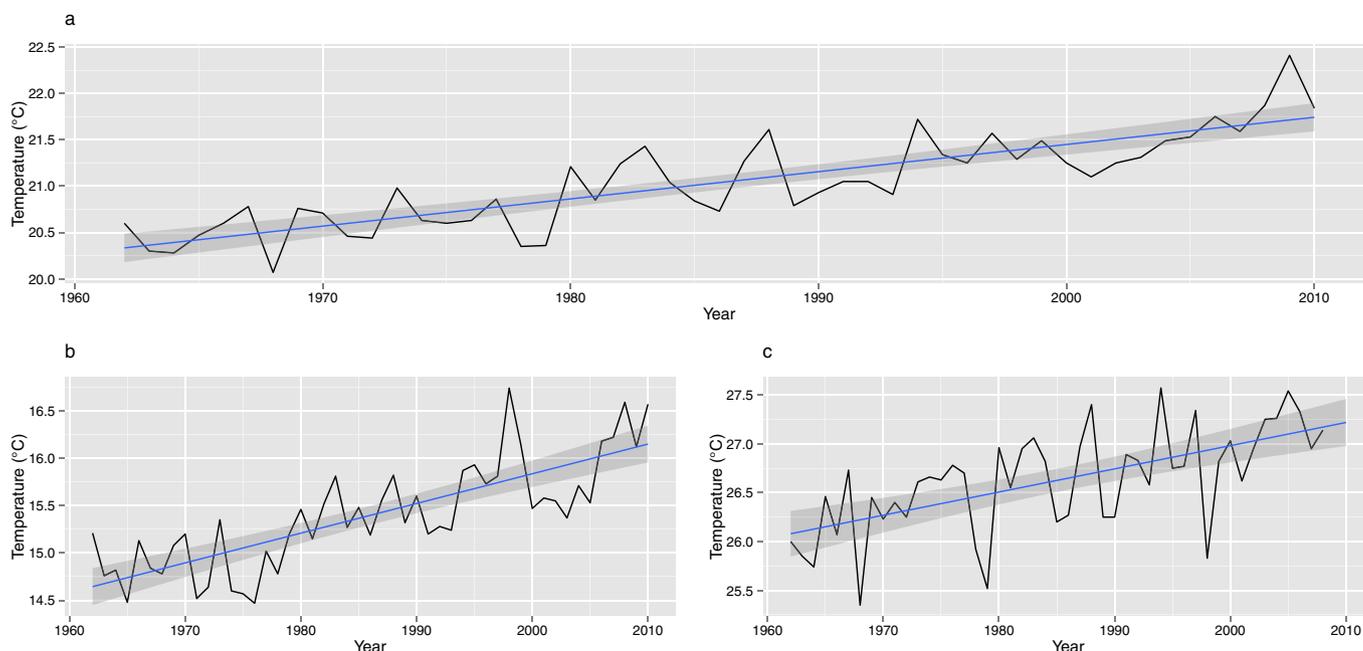


Fig. 3. Annual air temperature trends for the northern arabica growing regions of Tanzania. Temperatures are the mean (a), mean minimum (b) and mean maximum (c) for the growing season (October–September) for the period 1962–2010. A linear regression line with an associated confidence band of 95% is fitted to each series.

which are significant (P -value: <0.05) were then further investigated using time series analysis and non-linear regression in order to determine subtleties in the relationships, trends and boundaries. Given that individual models may contain inaccuracies and misspecifications, the use of two separate forecasting methods helps minimize such limitations (Adhikari, 2015). In order to account for observed trends in the data, an ARIMA (p,d,q) model was built and used for forecasting. Pioneered by Box and Jenkins (1970), the model provides a foundation for almost all statistical forecasting methods and assumes that present data are functions of the past data errors and data points. Although ARIMA models are particularly efficient in forecasting time series, accuracy is compromised with non-linear processes (Zhang, 2003; Adhikari, 2015). The autoregressive component denoted by 'p', is the number of lags for which each point is affected by the predecessor. The degree of non-seasonal differences involved is represented by 'd', and 'q' is the order of the moving average parameters which is based on the past forecast errors. The autocorrelation functions (ACF) and partial autocorrelation functions (PACF) were used to identify plausible models. The model diagnostic was performed using Bayesian information criteria (BIC) and significance tests. The model with lowest BIC values, which were statistically significant, was then considered a good fit model. To account for the shortfalls of the ARIMA model, a non-linear regression was built using a sigmoid function. Diagnostic plots, the Shapiro–Wilk and the Runs Test were used to check for normality of the residuals in the non-linear regression. All statistical analyses were performed using R software version 3.0.2.

3. Results

3.1. Observed air temperatures and precipitation

The annual mean temperature during the growing season (T_{mean}) for each of the arabica growing regions depict similar increasing trends of $+0.30^\circ\text{C}/\text{decade}$ ($P=5.27\text{e-}11$) for Lyamungu, $+0.24^\circ\text{C}/\text{decade}$ ($P=1.72\text{e-}10$) for Arusha, $+0.25^\circ\text{C}/\text{decade}$ ($P=2.66\text{e-}09$) for Moshi and $+0.27^\circ\text{C}/\text{decade}$ ($P=3.42\text{e-}09$) for Mbeya in the southern highlands. It should be noted, how-

ever, that there is substantial missing data ($>8\%$) within the Mbeya series. As the observed trends are significantly comparable to the remaining areas, this dataset was excluded from the analysis so as to preserve the number of observations, rather than undertaking data interpolation. Thus, in combining the areas, mean warming for the arabica growing regions of Tanzania is $+1.42$ ($P=2.83\text{e-}14$) over the 49 year period. Importantly, this trend is primarily driven by substantial increases in the daily minima of $+0.31^\circ\text{C}/\text{decade}$ ($P=8.547\text{e-}12$), compared to $+0.24^\circ\text{C}/\text{decade}$ for daily maxima (T_{max}) ($P=1.177\text{e-}06$) (Fig. 3).

Two of the strongest El Niño events are evident in the temperature anomalies of 1978 and 1998. The long duration and heavy rainfalls which started in October 1997 and continued through May 1998, greatly reduced temperature extremes which is most evident in the significantly lower maximums and higher minimum temperatures. Temperatures during the two phenologically important phases of flowering and ripening also display gradual increases over the 49 year period. Most noteworthy is the more pronounced increases in minimum temperatures during flowering (T_{minF}) ($+0.35^\circ\text{C}/\text{decade}$; $P=8.65\text{e-}09$) and ripening (T_{minR}) ($+0.30^\circ\text{C}/\text{decade}$; $P=8.21\text{e-}11$), compared to the rise in maximum temperatures of $+0.20^\circ\text{C}/\text{decade}$ ($P=0.011$) (T_{maxF}) and $+0.27^\circ\text{C}/\text{decade}$ ($P=2.53\text{e-}06$) (T_{maxR}), respectively. Maximum temperatures are also characterized by much greater inter-annual variability, particularly during the flowering season. While rainfall patterns have greater intra- and inter-annual variability, there is a decreasing trend over the 49 year period for each of the rainfall indices (Fig. 4). Precipitation during the crop year (P_{yr}) has decreased by $-40\text{ mm}/\text{decade}$ ($P=0.1347$). There is also a decline in rainfall during the dry season (P_{dry}) ($-7.1\text{ mm}/\text{decade}$; $P=0.0981$), and a decrease of $-19.7\text{ mm}/\text{decade}$ ($P=0.301$) during the flowering period (P_{F}). These trends are, however, not statistically significant. The trend of anomalies for the crop year (Fig. 4b) also substantiates that below average rainfall is occurring more often. For instance, 44% of years had below average rainfall for the 25 year period between 1962 and 1986, whereas 66% of all years had below average rainfall between the period 1987 and 2010.

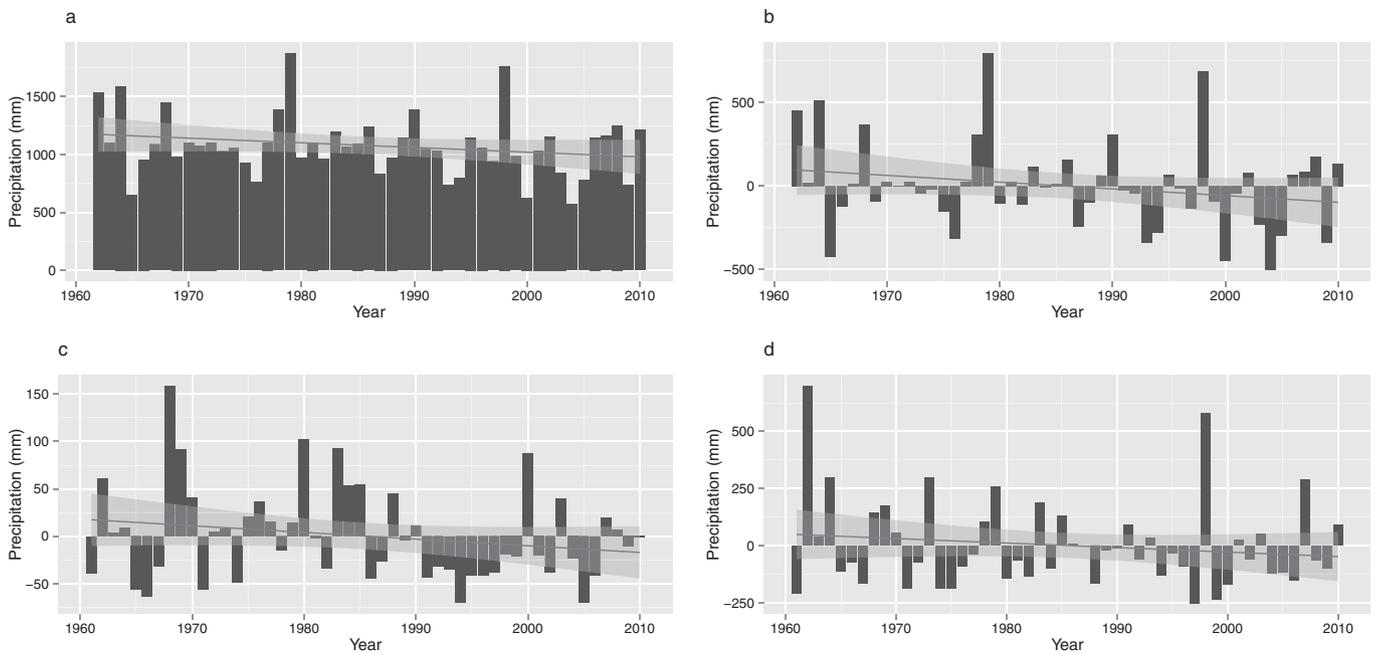


Fig. 4. Precipitation trends for the northern arabica growing regions of Tanzania. Trends are for the period 1960–2010 and represent the rainfall for the crop year (October–September) (a), anomalies for the crop year (b), anomalies for the dry season (June–September) (c) and anomalies for the flowering stage (October–February) (d). A linear regression line with an associated confidence band of 95% is fitted to each series.

Table 1

Pearson correlation values for the yield and production data series and the temperature variables.

Source	T_{\min}	T_{\max}	T_{mean}	$T_{\min F}$	$T_{\max F}$	$T_{\text{mean} F}$	$T_{\min R}$	$T_{\max R}$	$T_{\text{mean} R}$
FAOton	-0.226	0.118	-0.088	-0.175	0.090	-0.050	-0.236	0.126	-0.051
FAOkgha ⁻¹	-0.756**	-0.473**	-0.721***	-0.645***	-0.264*	-0.642***	-0.702***	-0.432*	-0.638***
NBS-ton	-0.649**	-0.310	-0.604**	-0.593**	-0.197	-0.548**	-0.636**	-0.272	-0.545**
NBSkg ha ⁻¹	-0.741***	-0.454**	-0.752***	-0.708***	-0.246	-0.661**	-0.694***	-0.459*	-0.692***
TCB-ton	-0.604**	-0.355	-0.650**	-0.545**	-0.179	-0.509**	-0.539**	-0.323	-0.559**
TCBkg ha ⁻¹	-0.585**	-0.422*	-0.682**	-0.557**	-0.169	-0.506**	-0.486**	-0.452*	-0.611**

* $P < 0.05$.

** $P < 0.01$.

*** $P < 10^{-6}$.

3.2. Trends in coffee production

All three production series exhibit very similar trends, with a correlation between the data sources ranging from $r=0.60$ to $r=0.80$ ($P < 0.000455$) (Fig. 2). Fitting a linear regression smoothing line with confidence intervals illustrates a slight insignificant decreasing trend within each of the time series. However, there is an apparent decreasing trend in the yield when planted area is taken into consideration (Fig. S1). External factors such as pest and disease stress, economic liberalization programmes and reforms implemented in 1990, as well as aging coffee trees, are thought to contribute to lower yields and quality (Baffes, 2003; Jaramillo et al., 2011). In addition, a substantial increase in planting area implemented in 2004 should account for some yield loss for the subsequent four years until those plants reach bearing maturity. However, even when this cultivated area and expansion in the southern highlands occurred (equating to approximately 50% of total production with the remainder of production from the northern highlands) yields did not increase. Furthermore, irrespective of the latter 6 years of the reference period, a highly significant ($p=0.000473$) decreasing trend is still observed for the period 1962–2003.

Supplementary material related to this article found, in the online version, at <http://dx.doi.org/10.1016/j.agrformet.2015.03.005>.

3.3. Crop-climate interaction and forecasting

All datasets, except FAOTON, confirm that out of the selected climatic variables, temperature has the greatest correlation with coffee production, with increasing temperature resulting in a significant loss of yield (Table 1). Contrary to the typical constraints found in coffee physiology research (e.g., temperature and drought stress; DaMatta et al., 2008), T_{\min} was consecutively the most significant climatic variable which determines coffee yield and production in each of the datasets, followed closely by T_{mean} . While T_{mean} has a strong correlation to coffee in several of the series, trends in mean temperature are largely driven by increasing minimum temperatures and thus are comparatively correlated with yield and production. Thus, more emphasis needs to be given to the difference between temperature boundaries (T_{\max} and T_{\min}), so as to determine which climatic variables have the greatest change and impact on coffee. The only precipitation variable which is slightly correlated to yield and production is the number of rain days during the flowering season (PD_F). Whilst not statistically significant, the interaction with each dataset indicates that if the rainfall is dispersed over a greater number of days during flowering, there is a negative impact on yield and production (Table 2).

The next most significant climatic variables are $T_{\min F}$ and $T_{\min R}$. These relationships reinforce the notion that the increasing T_{\min} have a significant influence in the physiology of arabica plant

Table 2
Pearson correlation values for the yield and production data series and the rainfall variables.

Source	P_F	P_{dry}	P_{yr}	SD	PD _{short}	PD _{long}	PD _F
FAOton	-0.204	-0.201	-0.340**	-0.222	-0.170	-0.290	-0.229
FAOkg ha ⁻¹	-0.024	0.196	-0.001	0.005	-0.073	-0.177	-0.308
NBS _{ton}	0.015	0.122	0.054	0.014	-0.028	0.200	-0.228
NBSkg ha ⁻¹	0.036	0.248	0.130	0.069	-0.076	0.019	-0.244
TCB _{ton}	-0.074	0.209	-0.108	-0.114	0.089	0.276	-0.473
TCBkg ha ⁻¹	-0.061	0.290	-0.04	-0.031	0.230	0.148	-0.464

* $P < 0.05$. *** $P < 10^{-6}$.

** $P < 0.01$.

growth and production in each of the phenological phases. Six separate multiple regression models were subsequently run in order to investigate the relationship between the changing climate and coffee production. To derive a usable model for the crop-climate interaction, one dataset (FAOSTAT) was then subsequently chosen based on data quality and the number of observations. Despite the insignificant correlations between the production data of the FAOSTAT dataset, the calculated yield data show very significant relationships with the climate data, akin to the correlations of the other two yield datasets. The yield data from the FAOSTAT were therefore used, since this is the longest dataset and quality can be verified by comparing the correlation results of the other two datasets. When this relationship is analysed linearly, with every 1 °C increase in T_{min} , there is a loss of $-137 \pm 16.87 \text{ kg ha}^{-1}$. This model explains 57% of the variation ($R^2 = 0.57$) and is highly significant at $P = 1.8e-10$. According to all subsets regression, adding a second predictor variable introduces PD_F which has a negative (-1.58 kg ha^{-1}) effect on yield ($P = 0.02$). However, the addition of a second and third predictor variable does not contribute to any further explanation of variance ($R^2 = 0.42$) and the unnecessary predictors add noise to the estimation of other quantities. The correlation and regression analyses allowed for successful data mining, however, in order to derive a more biologically meaningful result, this relationship was investigated using non-linear (logistic) regression with the following equation:

$$\text{kg ha}^{-1} = \frac{499.89}{\{1 + \exp[-(38.56 \pm 2.37 \times T_{min})]\}}$$

The reference period temperature was used and extrapolated from 14 °C to 18 °C, which roughly corresponds to the period 1950–2060. Similar to biological growth functions, a sigmoid curve best describes this interaction (Fig. 5). The non-linear nature of the curve allows the natural cycle of the plant to be modeled with the early lag and exponential phase, a linear phase and a diminishing or

saturation phase. It is evident that yield is greatest when the minimum temperatures are on the lower end of the spectrum. As the temperature progresses from the upper asymptote, the maximum rate of decrease is reached at the inflection point at approximately 16.2 °C. The curve then progresses with decreased deceleration through the saturation phase. Whilst these higher temperatures (17–18 °C) suggest they would be unsuitable for *C. arabica*, limited cultivation would still be possible.

Further to the logistic regression, an auto-regressive integrated moving average (ARIMA) (5,1,2) (p,d,q) model was selected for the temperature time series. Using this model for forecasting, T_{min} will be 16.8 °C and 17.7 ± 0.26 °C by the years 2030 and 2060, respectively, (MAPE = 1.4) (Fig. 6). These forecasted temperatures were then used as regressors against yield in the ARIMA (5,1,5) model (MAPE = 8.6). Importantly, the model incorporates the trends of T_{min} over the past 49 years for the forecast. This timespan includes influential events such as the global warming hiatus of the late 1990's, which may indeed result in more conservative future estimates (Watanabe et al., 2014). The model forecast indicates that by 2030 the average coffee yield will drop to $244 \pm 41 \text{ kg ha}^{-1}$ ($P = 8.45e-09$) (Fig. 7). The logistic regression model also indicates similar decreases in yield once temperatures approach 17 °C and 18 °C. Should the climate progress in this observed manner, without adaptation strategies or substantial external inputs, it is tentatively suggested that coffee production will likely drop to $145 \pm 41 \text{ kg ha}^{-1}$ ($P = 8.45e-09$) by 2060 and possible critical levels beyond that (Fig. 7).

4. Discussion

4.1. Context and implications

Our results suggest that the gradually increasing T_{min} in Tanzania may have a more pronounced impact on yield than stress from

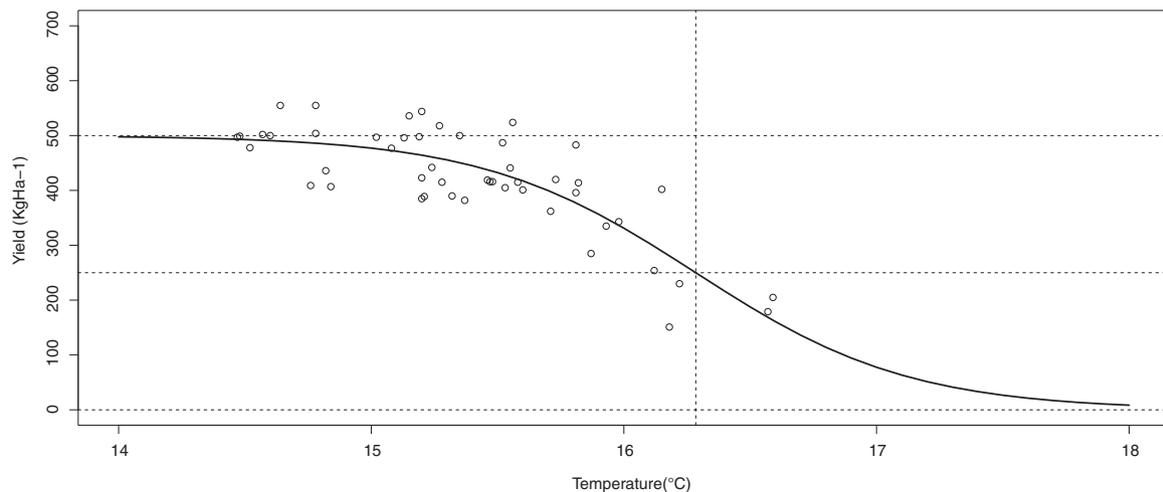


Fig. 5. Non-linear model of yield regressed by minimum temperature, extrapolated to 18 °C.

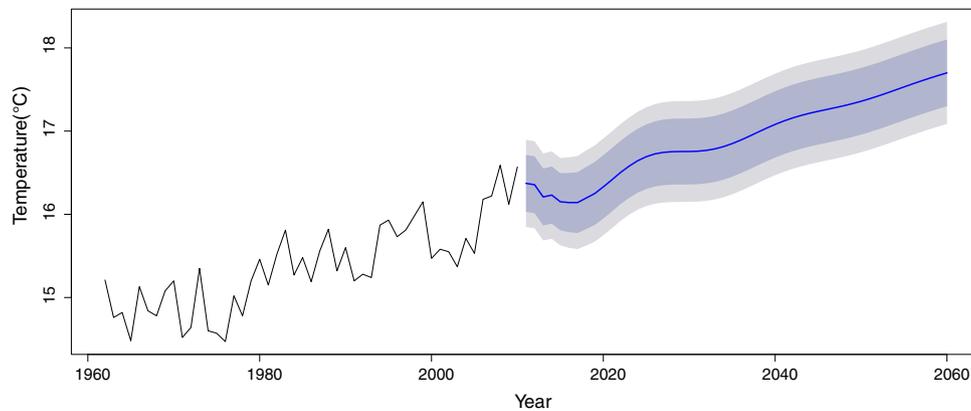


Fig. 6. ARIMA (5,1,2) model with forecasted minimum temperature for the period 1962–2060, with confidence vs. prediction intervals.

extreme minima (lowest annual temperatures) and maxima (highest annual temperatures), particularly over the longer term. The observed mean temperatures in the afro-montane regions of Tanzania's northern highlands seem to have reached the upper limit of the mean temperature bracket (18–21 °C) suitable for coffee cultivation (Alègre, 1959) (Fig. 3). As indicated in the temperature trends of each phenological phase, these increases are substantially driven by rising daily T_{\min} .

In order to derive a more biologically meaningful regression and to achieve a more robust extrapolation, we fitted a sigmoid curve to the data (Fig. 5). The curve highlights the importance of the low T_{\min} near the upper asymptote. As temperatures warm, yields decrease until the inflection point at 16.2 °C; thereafter the rate of yield decrease is slowed. Taking previous trends into consideration, the ARIMA (5,1,2) model and forecast for T_{\min} indicate that these temperatures will approach 17 °C by the year 2030 and surpass it by 2040 (Fig. 6). This is in accordance with the GCM forecasts and IPCC projections for the region; corresponding to the RCP 6.0 (roughly equivalent to the A1B emission scenario) (Meinshausen et al., 2011), associated with a 2.8 °C rise by 2100. Continuing from the inflection point of the sigmoid function, although the latter section of the curve suggests that coffee is still viable for cultivation under these conditions in the northern Tanzanian highlands, yields would be significantly lower. This confirms the trends observed in the ARIMA (5,1,5) model of forecasted yield (Fig. 7). However, given that the ARIMA model is built using the forecasted T_{\min} , these slightly lower minimum temperatures result in projected values that have a more positive outlook for future production than that provided by the sigmoid function. Based on this model, the yield would drop to $145 \pm 41 \text{ kg ha}^{-1}$ ($P=8.45\text{e-}09$) by the year 2060

(Fig. 7), as opposed to falling below 100 kg ha^{-1} (Fig. 5). When investigated linearly over the data period, yield loss per degree Celsius increase in T_{\min} ($137 \pm 16.87 \text{ kg ha}^{-1}$, $P=1.80\text{e-}10$) is more substantial than when past trends and cycles are considered using the ARIMA model. In the natural environment, the plant would not respond linearly to this change; we thus suggest that the non-linear and ARIMA functions are better representations of future change. With respect to coffee plant phenophases, our results suggest that yields are most strongly influenced by responses to atmospheric stimuli during the growing and flowering seasons.

Against expectations, we found that trends in the rainfall and associated phenological indices, including a precipitation lag of up to two years prior to the event, had little effect on yield, except for the number of rain days during flowering. When included as a second predictor in the multiple regression model, PD_F has a negative correlation with yield. The relationship suggests that if rainfall is dispersed on a greater number of days during the flowering period, it would negatively impact yields. This is in accordance with current research on the physiological mechanisms associated with coffee flowering. A dry phase corresponding to quiescence, lasting up to four months, is required by the plant to stimulate flowering (Crisosto et al., 1992; Gutiérrez and Meinzer, 1994). The occurrence of sporadic and low-intensity rains over the flowering period, and particularly toward the later-phases of flower bud development, is thought to be one of the major factors responsible for unsynchronized fruit ripening (DaMatta et al., 2008). In Tanzania, a greater number of rain days during the flowering period may thus disrupt the processing, quality and production of coffee. The dissociation of other rainfall indices with yield variability in this study may be attributed to the superseding negative effect from an insufficiently

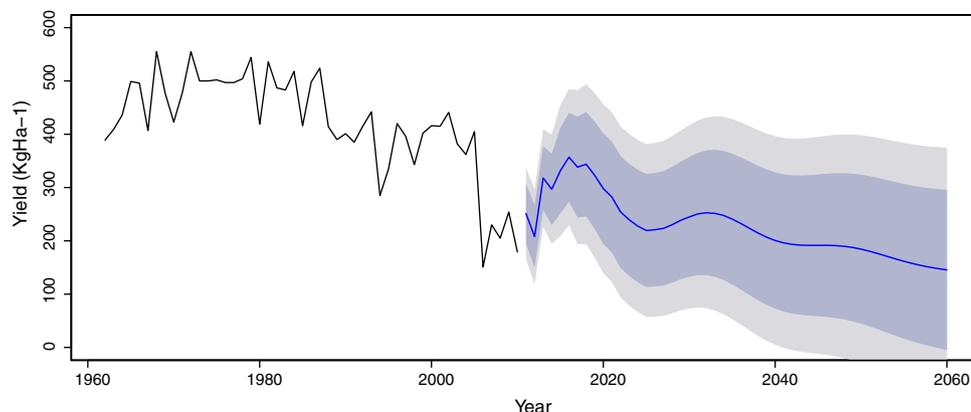


Fig. 7. ARIMA (5,1,5) model with forecasted yield based on extrapolated minimum temperatures for the period 1962–2060, with confidence vs. prediction intervals.

cool season. This does not suggest that the remaining precipitation variables analysed have no association with growth periodicity or phenology, but rather that the relatively modest changes in rainfall have little or no relation to the longer-term yield and production variability.

The particular sensitivity of *C. arabica* to increasing T_{\min} may be crucial for the design of climate-smart practices and adaptation strategies in coffee agroforestry settings. While shading is an important practice which benefits agroforestry, tree species and spacing becomes more important if the mean temperature is close to, or exceeds the optimal temperature bracket for growth (Lin, 2010). Shading provides a buffer for minima and maxima temperature extremes of between 2 and 4 °C, which is desirable in many marginal coffee growing areas (Vaast et al., 2006). However, the conservation of heat during the night or cool season effectively prevents an adequate temperature drop, which is necessary for the reproductive growth processes in several crops (Peng et al., 2004; Nagarajan et al., 2010; Bapuji Rao et al., 2014). These results therefore challenge the common notion that shade trees are always a beneficial aspect of climate change adaptation. The current T_{mean} had already surpassed the upper limit of the optimum temperature (21 °C) by 1995, and is currently fast approaching the upper limit of favorable growth for quality arabica (23 °C) (Barros et al., 1997; Teixeira et al., 2013) (Fig. 3). While some areas are expected to benefit from this change, the optimum coffee-producing zone would need to shift upwards altitudinally by 150–200 m in the northern highlands of Tanzania, so as to sustain coffee quality and quantity. However, this pushes coffee into a higher altitudinal zone that currently hosts substantial biodiversity of (mostly protected) forest species (Hemp, 2005), thus limiting upslope coffee expansion in northern Tanzania and indeed much of the coffee regions in tropical countries.

The findings presented here have strong parallels with other global studies investigating the effect of climate change on temperate fruit and nut trees (e.g., Luedeling, 2012; Lobell et al., 2013; García-Mozo et al., 2014) and on tropical crops (e.g., Peng et al., 2004; Nagarajan et al., 2010; Bapuji Rao et al., 2014). In particular, it is emphasized that rapidly rising T_{\min} are driving changes to chilling requirements and phenology, with the greatest consequential impact on fruit production in warm climates (Luedeling, 2012). Our results correspond with those of Gay et al. (2006), who demonstrate that temperature, and particularly warming winter temperature, is the most detrimental climatic variable for coffee production in Veracruz, Mexico. This is further supported by earlier findings that increasing temperatures, rather than extreme air temperatures associated with high vapor pressure deficit (VPD) and high solar radiation, are responsible for declining coffee yields during the active growth period (Barros et al., 1997; Silva et al., 2004). Using a modeling approach, Mulangu and Kraybill (2013) provide a very similar scenario of coffee revenue losses on Mt. Kilimanjaro, ranging between 28.8% and 63.1% by 2050, depending on best and worst case scenarios, respectively. Further, maximum entropy (MAXENT) models suggest that the suitability of arabica will decrease by 20–30% in Tanzania by 2050 (Läderach et al., 2012).

4.2. Outlook

Mindful of the sensitive agroclimatic relationship described here, we highlight other major global *C. arabica* growing regions which face similar climate change scenarios. All three major tropical rainforest regions have experienced warming trends over the period 1960–1998: 0.26 ± 0.07 °C/decade – America; 0.29 ± 0.06 °C/decade – Africa; 0.22 ± 0.04 °C/decade – Asia (Malhi and Wright, 2004). Most importantly, trends of increasing T_{\min} are becoming more prevalent, particularly in mountainous regions (Quintana-gomez, 1999; Vuille et al., 2003). In the south east-

ern states of Brazil, the world's largest coffee producer, T_{\min} have increased by 0.8 °C/decade over the past 6 decades (Marengo and Camargo, 2008) – more than double the rate of change for T_{\max} (de los Milagros Skansi et al., 2013). At Monteverde, Costa Rica, mean daily T_{\min} are rising while T_{\max} are declining (Pounds et al., 2006). Similarly, substantial T_{\min} increases have occurred in Colombia and Venezuela since 1960 (Quintana-gomez, 1999). Colombia is consistently the second largest producer of *C. arabica* in the world, yet is one of several countries with an average yield decline of 30% since 1990 (FAOSTAT, 2014).

Studies focusing on the African highlands have also reported increasing T_{\min} (e.g., New et al., 2006; Omondi et al., 2014). Ethiopia, the genetic origin and largest African producer of *C. arabica*, has experienced increases in T_{\min} of between 1 °C (Asela) and 1.4 °C (Negele) per decade (Mekasha et al., 2014). Negele is within the Yirgacheffe region, where some of Ethiopia's finest coffees originate. A warming trend of 0.32 °C and 0.21 °C/decade for cool nights has been observed in Ethiopia and Kenya, respectively (Mekasha et al., 2014; Omondi et al., 2014). In addition, Jaramillo et al. (2013) calculated temperature increases of 0.05 °C/decade for a coffee region in Kenya (Kiambu District) over the period 1929–2009. However, when focussing on the most recent period (1979–2009), a much steeper $T_{\text{mean,min,max}}$ warming trend (0.2 °C/decade) is recorded for Kericho (Omumbo et al., 2011). Uganda has likewise experienced more rapid warming of T_{\min} than T_{\max} over the period 1960–2008 (Nsubuga et al., 2014). Considering the greater East Africa region, increasing trends for warm nights are the most spatially coherent variable, with a substantial increase in the number of nights per year exceeding the 90th percentile threshold (Omondi et al., 2014). While there is a general warming trend for India (a substantial arabica producer in Asia), T_{\min} and T_{\max} trends are heterogeneous and localised, particularly in the Western Ghats mountain range where the majority of *C. arabica* is grown (Panda et al., 2014). The arabica growing regions mentioned here is not a complete list of all those facing T_{\min} warming trends, but rather those for which critical climate analyses have been published in reputable journals. Each arabica growing region exists in a unique agroecological niche and is associated with different access to inputs, management systems, coffee species and varieties, as well as planting systems and programmes; all of which makes yield trends highly heterogeneous (Jha et al., 2014). Furthermore, when considering coffee production globally, *Coffea canephora* (Robusta), which is hardier and climatically more tolerant than arabica, is often included in country production figures, consequently smoothing trends. For instance, Brazil has seen a 112% rise in production over the period 1996–2010, owing predominantly to intensification (Jha et al., 2014). The global shift in production over this period was largely regional; 45% of countries experiencing decreases were in Africa, whereas Asian countries (which grow and produce the majority of robusta) were responsible for the 35% of nations with increased production (Jha et al., 2014). Observed arabica yield losses such as in this case in Tanzania, may thus not yet be clearly evident elsewhere, despite possibly being at risk.

5. Conclusion

Using several statistical analyses, we find that gradually increasing T_{\min} are significantly reducing arabica coffee yields in Tanzania. T_{\min} have increased by 0.31 °C/decade ($P=8.547\text{e-}12$), over the past 49 years. For every 1 °C rise in T_{\min} , yields have dropped by 137 ± 16.87 kg ha⁻¹ ($P=1.80\text{e-}10$). Our ARIMA model forecast indicates that if trends continue as has been observed during recent decades, assuming without innovative agricultural adaptation strategies, then *C. arabica* production in Tanzania will drop to 145 ± 41 kg ha⁻¹ ($P=8.45\text{e-}09$) by the year 2060. However, consid-

ering the limitations of the linear regression and ARIMA models, the more applicable non-linear regression model suggests a less optimistic future, with yields dropping below 100 kg ha^{-1} by the year 2060. Given that coffee production supports the livelihoods of more than 2.4 million individuals in Tanzania, and up to 25 million families worldwide, the forecast presented here has major livelihood implications, especially for countries in similar arabica growing agroclimatic situations (e.g., Brazil, Colombia, Costa Rica, Ethiopia and Kenya). To strengthen the confidence and relevance of our findings, it would be very valuable if similar analyses were to be conducted in other coffee growing countries. This requires accessing long-term climate and production data that were not available to the authors at the time of this study. Our observations on the role of minimum temperature and diurnal temperature variation do query the popular belief that shade trees are required for climate change adaptation in warmer areas. To provide sound recommendations on shading, further studies are required to better understand the impact of micro-climate dynamics of shade trees in these marginal coffee production areas. Although substantial governmental interest is invested in the coffee sector of major coffee producing countries, robust analyses of coffee and climate change at the regional or national scale have until now been lacking. In addition, there are several external controls such as aging plantations (infrastructure) and socio-economic/political factors that have contributed to coffee yield losses in the tropics. However, notwithstanding these other challenges to the coffee industry, the ability to discriminate the relative importance of several atmospheric variables is most essential for directing efforts to develop crops with better climate tolerance, identifying key drivers for inputs into crop-climate models, and providing applicable site-specific adaptation strategies. This study provides the first historical 'on the ground' evidence that climate change is already impacting the arabica coffee sector in the East African Highlands region. Furthermore, we emphasize key arabica growing regions which may have already suffered yield losses due to recent T_{\min} increases, or may so in the near future. It may give the coffee sector the hard numbers required to encourage the public and private-sectors to invest in climate change adaptation strategies that will better sustain this important industry and the livelihoods of millions of smallholder farmers who depend on it.

Author contributions

A.C.W.C. and P.J.A.V. conceived the study. A.C.W.C. analysed the data. A.C.W.C., P.J.A.V., P.L., L.T.P.J. and S.W.G. wrote the paper.

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