Influence of climate change and variability on *Coffea arabica* in the East African highlands

Thesis

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Abstract

Plant development is inherently linked to meteorological variability. The phenology, distribution and production of crops and wild relatives has already altered in response to climate change. Recent years have produced the warmest mean annual global temperatures since 1880, with 2016 setting the highest record thus far. Such profound changes have sparked investigations into the impact of temperature and rainfall on crop development, particularly those with profound economic importance such as coffee (*C. arabica*). The crop is a fundamental source of income for smallholder farming communities and governments throughout the tropical highlands. However, the impact of climate change on *C. arabica* has yet to be quantified using empirical data in East Africa, leaving uncertainty in the cultivable future of the crop. Therefore, the objective of this thesis is to investigate the influence of climate change and variability on *C. arabica* yields and phenology in East Africa.

Using a spatio-temporal approach, trends and relationships between coffee performance and meteorological variables were analysed at different scales and time periods ranging from the macroclimatic national scale (49 year), to the meso- and microclimatic farm level (3 year) scale, and finally to the microclimatic canopy and leaf level (hourly) scales. Data from all three climatic continua reveal for the first time that temperatures, and particularly rapidly advancing night time temperatures, are having a substantial negative impact on *C. arabica* yields. Forecasting models based on these biophysical relationships indicate that by the year 2050, smallholder farmers would on average harvest approximately 50% of the yield they are achieving today. Warming night time temperatures are also responsible for advancing ripening and harvest phenology. As a result, bean filling and development time is reduced, thereby potentially resulting in lower quality coffee. Trends in precipitation do not appear to have any substantial impact on *C. arabica* yields or harvest phenology, however, it is proposed that rainfall would act synergistically with temperatures to influence plant development and other phenological phases such as flowering. Finally, thermography is introduced as a novel complementary technique to rapidly analyse the suitability of different agroecological systems on coffee physiology at the leaf level. High temporal resolution (hourly) data, illustrate the success of the method in variable meteorological and environmental conditions. The findings contribute to advancing the protocol for use at the canopy and plantation

level on coffee, so that appropriate microenvironment designs and adaptation mechanisms be put in place to accommodate climatic change.

Avoiding increments in night time temperatures is key to maintaining or improving yields and fruiting development. Farming at higher altitudes and novel agroforestry systems may assist in achieving lower night time temperatures. Importantly, data reveal that careful analysis of various cropping systems, particularly at lower altitudes, is critical for providing suitable microenvironments for the crop.

Acknowledgements

This thesis was driven by curiosity. Each person has played an important role in stimulating this inquisitiveness and therefore I express my sincere gratitude. In particular, I thank; Piet van Asten, Peter Läderach, Stefan Grab and Laurence Jassogne for their guidance, support and most importantly, inspiration. I am not only indebted to the countless hours spent discussing topics, often till the early hours of the morning, but also extremely grateful for the element of fun and excitement brought to the research. A sincere thank you to Philippe Vaast who not only provided constant guidance, but was also my first point of contact in the industry, initiating the collaborations and relationships we have today.

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Abbreviations, symbols and definitions

Abbreviations

ACF	Autocorrelation Functions
AR5	5th Assessment Report of the IPCC
ARIMA	Auto-Regressive Integrated Moving Average
BIC	Bayesian Information Criteria
CRU	Climate Research Unit
CWSI	Crop water stress index
DAF	Days After Flowering
ENSO	El Niño-Southern Oscillation
FAOSTAT	Food and Agricultural Organization of the United Nations
GCM	General Circulation Model
GDD	Accumulated Growing Degree Days
GDP	Gross Domestic Product
GEC	Global Environmental Change
ICO	International Coffee Organization
IPCC	United Nations Intergovernmental Panel on Climate Change
JD	Julian Day
MAPE	Mean Absolute Percentage Error
MAXENT	Maximum Entropy Model
MIR	Middle Infrared
NBS	Tanzanian National Bureau of Statistics
NOAA	National Oceanic and Atmospheric Administration
PACF	Partial Autocorrelation Functions
PAR	Photosynthetically Active Radiation
RCP	Representative Concentration Pathways
SST	Sea Surface Temperature
TACRI	Tanzania Coffee Research Institute
TCB	Tanzania Coffee Board

VPD	Vapor Pressure Deficit

General symbols and definitions

Symbol	**Meaning**	**Unity**
C_P	Thermal capacity of air	$(J\ Kg^{-1}\ K^{-1})$
d	Characteristic leaf dimension	(m)
ε	Emissivity	(-)
γ	Psychrometric constant	$(kPa\ K^{-1})$
G	Boundary layer conductance	$(mmol\ m^{-2}\ s^{-1})$
g_1	Stomatal conductance derived from I_g and G	$(mmol\ m^{-2}\ s^{-1})$
gs	Stomatal conductance	$(mmol\ m^{-2}\ s^{-1})$
I_g	Stomatal conductance index	(-)
K_{in}	Incoming solar radiation	(Wm^{-2})
P_α	Air density	$(Kg\ m^{-3})$
PAR	Photosynthetically active radiation	$(\mu mol\ m^{-2}\ s^{-1})$
T_a	Air temperature	(°C)
T_{canopy}	Canopy air temperature	(°C)
T_{day}	Mean temperature during the day	(°C)
T_{dry}	Surface temperature of dry reference surface	(°C)
T_{leaf}	Leaf surface temperature	(°C)
T_{max}	Absolute maximum temperature	(°C)
T_{mean}	Absolute mean temperature	(°C)
T_{min}	Absolute minimum temperature	(°C)
T_{night}	Mean temperature during the night	(°C)
T_{wet}	Surface temperature of wet reference surface	(°C)
u	Wind speed	(ms^{-1})
r_{aH}	Leaf resistance to sensible heat transfer	$(s\ m^{-1})$
r_{aV}	Resistance to vapour transport in the boundary layer/air	$(s\ m^{-1})$

r_R	Virtual leaf resistance to radiative transfer	($s\ m^{-1}$)
s	Slope of the curve relating T_a with saturated vapour pressure ($Pa\ K^{-1}$)	($Pa\ K^{-1}$)
σ	Stefan Boltzmann Constant	($5.675\ 10^{-8}\ W\ m^{-2}\ K^{-4}$)
r_{HR}	Leaf resistance to sensible heat transport and radiative loss	(sm^{-1})
r_s	Leaf stomatal resistance	($s\ m^{-1}$).

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CHAPTER 1

GENERAL INTRODUCTION

1.1. Background

For almost two centuries after Charles de Bouvelles published the *Liber de sapiente* in 1509, plants were still regarded as passive organisms, incapable of sensation or any capacity for communication, behaviour or computation (Mancuso and Viola, 2015). Though a somewhat anthropocentric view still exists, plants are now accepted as complex organisms with evolving fields of study such as plant neurobiology (Mancuso and Viola, 2015). Compared to other organisms, the sessile nature of plants makes adaptation to environmental stresses even more remarkable, with considerable plasticity in their developmental and physiological behaviours (Brenner et al., 2006).

Plants face several persistent and novel challenges, though currently, none more pressing than climate change (Torquebiau et al., 2016). Plants have had to acclimate to the warmest temperatures since the year 1880, with each of the last three decades being successively warmer than any other (Mann et al., 2016). The impact of climate change on plant species is already well documented. Numerous extinctions have occurred, largely due to the inability to rapidly adapt to environmental change (Wiens, 2016). If trends continue as they have for the past several decades, the increase in global mean surface temperature is likely to surpass 2°C (RCP6.0) over the course of the 21st century (IPCC, 2014). Fluctuations in precipitation have been less apparent and forecasted changes will not be uniform (IPCC, 2014).

Coffee is no exception to this evolution. The plant is grown in nearly 60 intertropical countries, with the vast majority of countries located in Africa (ICO, 2015). Only two species are used for commercial purposes; *Coffea arabica* (*C. arabica*), grown under cool climatic conditions and *Coffea canephora* (*C. canephora*), which favours much warmer equatorial climatic conditions (Bertrand et al., 2016). The niche climatic requirements of *C. arabica* limit it to a narrow envelope of mountain highlands with an optimal temperature bracket of 18-21°C (Alègre, 1959). This inherently renders the species vulnerable to environmental change. In addition, mountain slopes offer limited cultivable land and also often host substantial biodiversity of protected species, which adds further pressure to the plant's adaptation potential (Hemp, 2006). Well managed plantations with correct pruning techniques, fertilization and cyclical rejuvenation (stumping), may lessen the biennial nature of the crop and extend the quality and quantity of production (Lambot and Bouharmont, 2009).

Ironically, due to superior beverage quality, *C. arabica* attains a much higher premium than *C. canephora* and accounts for ~60% of global production (ICO, 2015). The vast majority of this (>90%) is grown by smallholder farmers. In the 25-coffee growing countries in Africa, just over 12 million people rely on the crop for their livelihoods. This amounts to ~64% of the rural population (ICO, 2015). Thus, the influence that changing climatic conditions has had, and will have on coffee production, has attracted considerable investment and enquiry.

1.2. Problem analysis

There have been significant research efforts investigating the impact of climate change on *C. arabica* (e.g. Gay et al., 2006; Davis et al., 2012; Bunn et al., 2015; Rodrigues et al., 2016; Läderach et al., 2016). However, several factors ensure a complex interaction between these variables, thereby leaving a margin of uncertainty:

1. Fundamentally, smallholder farming systems are historically data poor and particularly so in East Africa. Consequently, to date, the anticipated impact of climate change on *C. arabica* is largely limited to *ex situ* experiments (Lima et al., 2013; Martins et al., 2016) or modelling studies based on downscaled global climate models (Davis et al., 2012; Bunn et al., 2015; Ovalle-Rivera et al., 2015; Läderach et al., 2016; Ranjitkar et al., 2016).
2. *C. arabica* is cultivated within a variety of cropping systems ranging from high throughput monocultures, to natural agroforestry associations (Bertrand et al., 2016). However, recent research has shown that the impact of climate change on the plant varies depending on the environment considered. Typical parameters such as shade, sunlight and altitude may either ameliorate or exacerbate the impact, depending on the agroecological system (Bertrand et al., 2016).
3. Together with physiological productivity changes, plants may exhibit substantial plasticity in the timing of biological events, or phenophases (i.e. budburst, flowering, ripening), utilized as an adaptation mechanism to environmental change. Despite considerable logistical and financial impacts this may have on the industry, the influence that changing temperature or precipitation patterns have had, or will have on *C. arabica* phenology, is still largely unknown.
4. Lastly, the adaptation of *C. arabica* to several different environments and cropping systems within the intertropical belt, may be attributed to the allotetraploidy of its genome, as well as the heterogeneity in newly developed cultivars and even wild relatives (van der Vossen et al., 2015; Aerts et al., 2017). These lines have vastly different tolerable limits and

production characteristics. However, the vast majority of *C. arabica* in production in East Africa today, is limited to traditional cultivars developed long ago by line selection within the Typica and Bourbon source varieties (van der Vossen et al., 2015). Therefore, the suitability, resilience or productivity of traditional varieties, particularly of those *in situ*, would be different to newly developed cultivars and may vary considerably under future change scenarios.

1.3. Research aims and objectives

The aim of this thesis is thus to quantify the influence, if any, that climate change has had and will have on *C. arabica* in the East African highlands. Specific questions which have not yet been fully addressed include:

1. How has the climate of *C. arabica* growing regions changed in East Africa over the past several decades and has this influenced yields?
2. What is the forecast of projected yields in this environment?
3. Do these relationships concur with those observed at the mesoclimatic scale?
4. How has climate change influenced the phenology of *C. arabica* and what does this mean for *C. arabica* farming systems and adaptation potential?

The study utilizes several different spatial and temporal continua to identify and subsequently verify observed relationships and trends.

1.4. Thesis outline and approach

The research starts with an investigation of long-term climatic and yield parameters at the national scale, thus minimizing noise from farming systems, varieties and agricultural practices (Fig. 1.1). Tanzania was selected for this analysis due to the availability of empirical data. Based on these relationships, several linear and biologically significant non-linear models are built to forecast the impact of climate change on yields to the year 2060. Novel relationships are identified which then spur on an inquisition of implications for the remainder of global *C. arabica* producing regions. From this national macroclimatic context, Chapter 3 focuses on these same parameters and interactions; however, the diversity of planting systems and shade levels are introduced at this level. High resolution microclimatic data are collected over a period of two years and an altitudinal (spatial) gradient is used to simulate progressive climate change *in situ*, under a mesoclimatic setting. Careful selection of commercial farming estates ensures agronomic practices and cultivars are kept homogenous over the transect. The timing of the plant's biological events is then the focus of Chapter 4. Using the same spatio-temporal transect, plant phenophases are then investigated in the context of different planting systems and the subsequent effect these systems have on the microclimate. These relationships are then forecasted based on models developed in Chapter 2, providing a preview of potential phenological variability under future climate change scenarios. With a greater understanding of the effects of climate change on *C. arabica* yields and phenology in the region, Chapter 5 delves further into the spatio-temporal continuum and focuses on dynamics at the microclimatic leaf level. By introducing thermography to the coffee physiology field, this chapter takes a more solutions-based approach and explores the potential of a novel method used to rapidly identify the physiological status of *C. arabica* under different cropping systems. The importance and potential of this method for assisting in climate change adaptation strategies and climate-smart cropping systems is discussed.

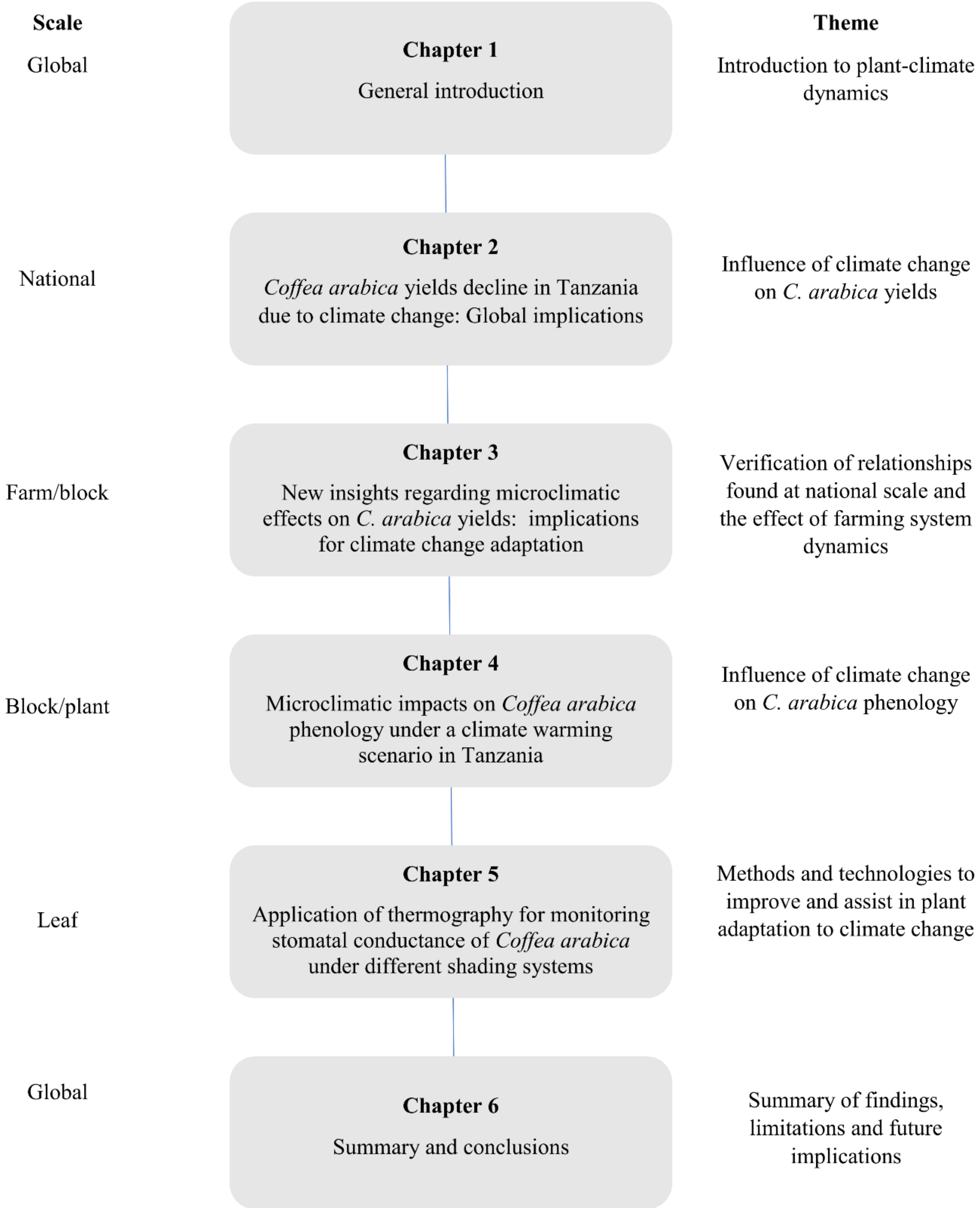

Fig. 1.1 Thesis structure

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CHAPTER 2

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, this study demonstrates 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 ± 16.87 kg ha^{-1} (P = 1.80e-10). According to the ARIMA model, average coffee production will drop to 145 ± 41 kg ha^{-1} (P = 8.45e-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.

Keywords: Agriculture, Minimum temperature, Phenology, Adaptation

2.1. 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 agroecological conditions in neighbouring 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) 6.0scenario (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. 2.1). Although progressive drying throughout the 20thcentury 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 projections (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.

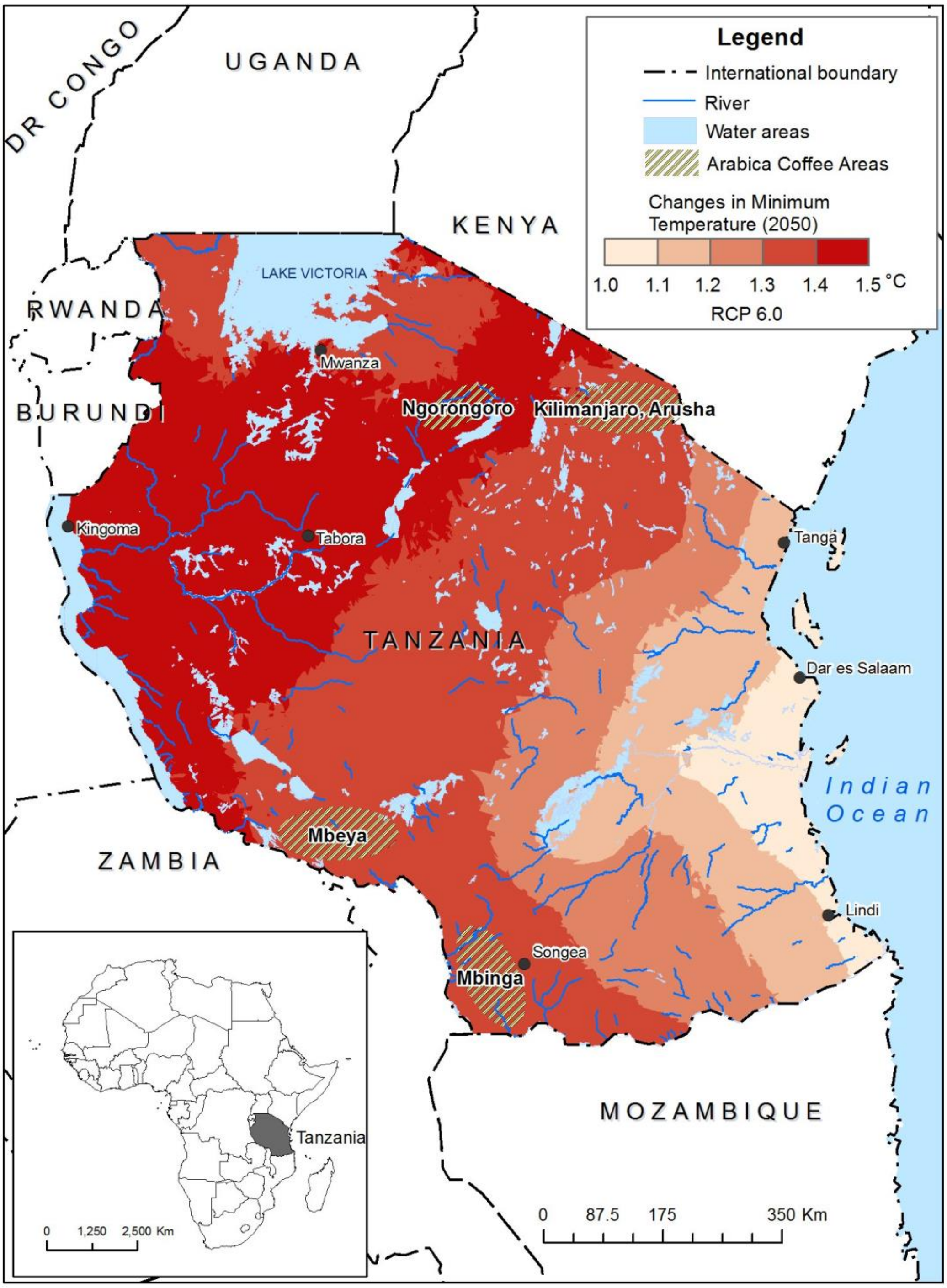

Fig. 2.1. Projected change in minimum temperatures for Tanzania to 2050. Future minimum temperature change is based on the Representative Concentration Pathway 6.0 (Meinshausen et al., 2011).

The objective of this study is to quantify the impact of climate change on Tanzania's arabica coffee production. The aim is 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). The phenotypic phase at which this relationship is most important is presented and this model is used to make climate and yield projections to 2060. Further to this, all other global *C. arabica* producing areas are reviewed and regions which have followed similar climatic trends are highlighted.

2.2. Materials and Methods

2.2.1. *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 Mbinga 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 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 are1–2 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. 2.2). 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.

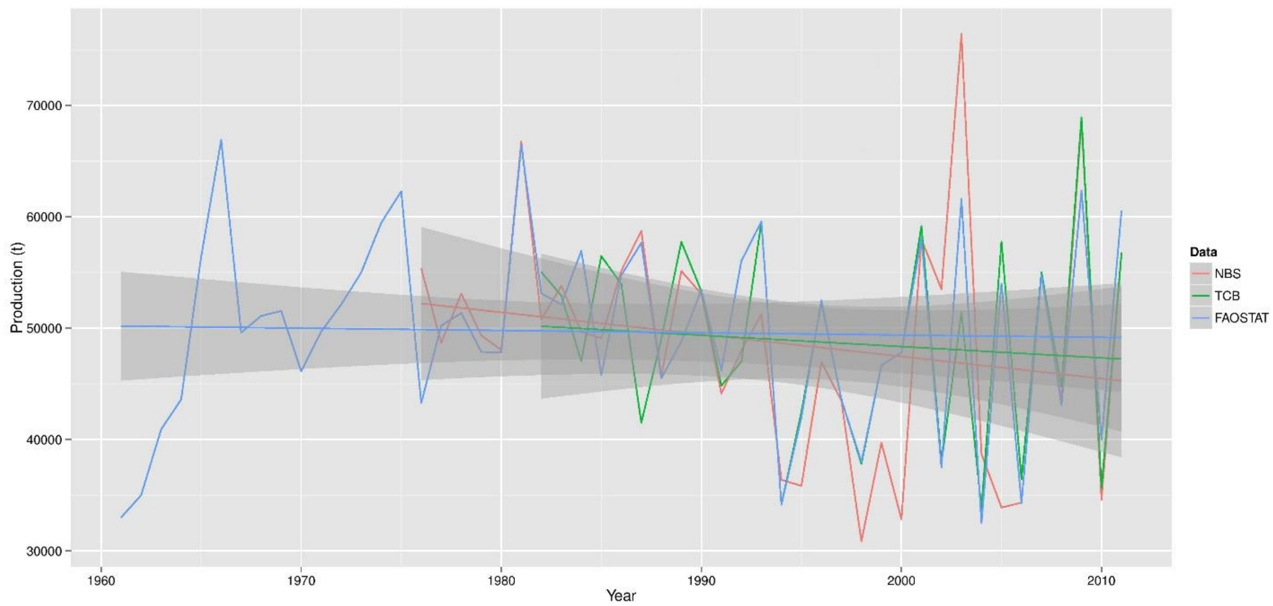

Fig. 2.2. Annual clean bean arabica production trends for Tanzania. Trends are for the period 1962–2012 (FAOSTAT), 1976–2012 (NBS) and 1976–2012 (TCB). A linear regression line with an associated confidence band of 95% is fitted to each series.

2.2.2. *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_{minF}), maximum (T_{maxF}) and mean (T_{meanF}) temperatures during flowering (October–February) and the mean minimum($\mathrm{T}_{\mathrm{minR}}$), maximum ($T_{maxR}$) and mean ($T_{meanR}$) 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 rain-fall 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.

2.2.3. 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 datamining 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 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 auto-regressive 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.

2.3. Results

2.3.1. *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°C/decade (P = 5.27e-11) for Lyamungu, +0.24°C/decade (P = 1.72e-10) for Arusha, +0.25°C/decade (P = 2.66e-09) for Moshi and +0.27°C/decade (P = 3.42e-09) for Mbeya in the southern highlands. It should be noted, however, 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 = 2.83e-14) over the 49-year period. Importantly, this trend is primarily driven by substantial increases in the daily minima of +0.31°C/decade (P = 8.547e-12), compared to +0.24°C/decade for daily maxima (T_{max}) (P = 1.177e-06) (Fig. 2.3).

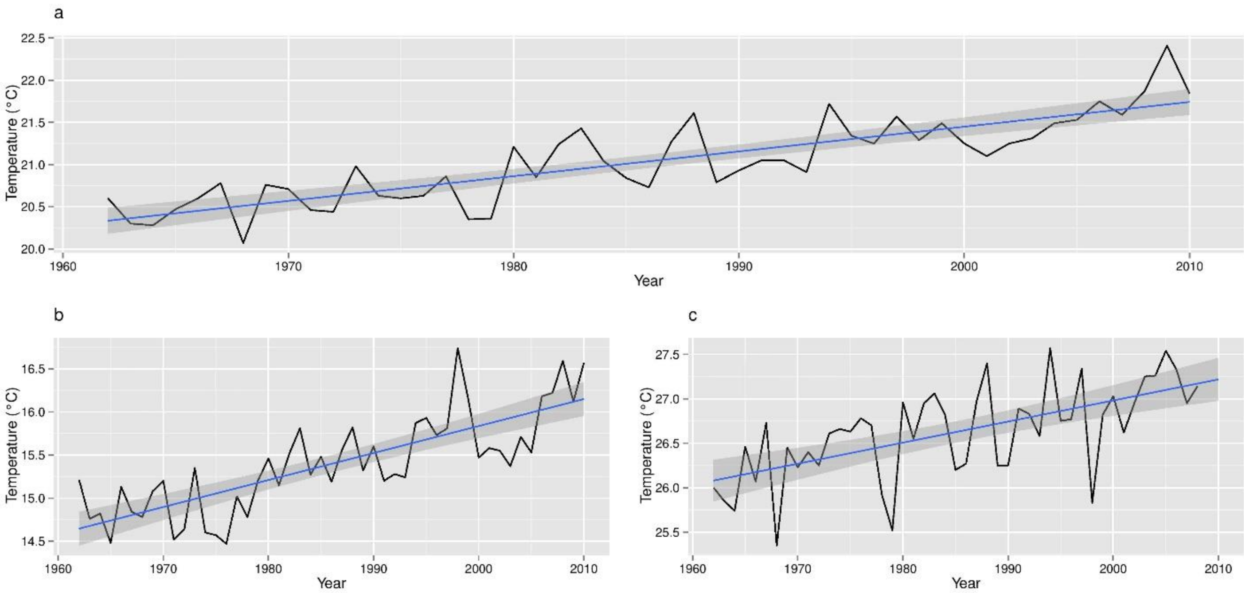

Fig. 2.3. Annual air temperature trends for the northern arabica growing regions of Tanzania. Temperatures are the mean (a), mean minimum (b) and mean maximum (c) for the growing season (October–September) for the period 1962–2010. A linear regression line with an associated confidence band of 95% is fitted to each series.

Two of the strongest El Nino 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°C/decade; P = 8.65e-09) and ripening (T_{minR}) (+0.30°C/decade; P = 8.21e-11), compared to the rise in maximum temperatures of +0.20°C/decade (P = 0.011) (T_{maxF}) and +0.27°C/decade (P = 2.53e-06) (T_{maxR}), respectively. Minimum temperatures are also characterized by much greater inter-annual variability with a coefficient of variation of 2.9%, compared to 1.5% for maximum temperatures, particularly during the flowering season (3.1 and 2.2% respectively). 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. 2.4). Precipitation during the crop year (P_{yr}) has decreased by −40 mm/decade (P = 0.1347). There is also a decline in rainfall during the dry season (P_{dry}) (−7.1 mm/decade; P = 0.0981), and a decrease of −19.7 mm/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. 2.4b) 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.

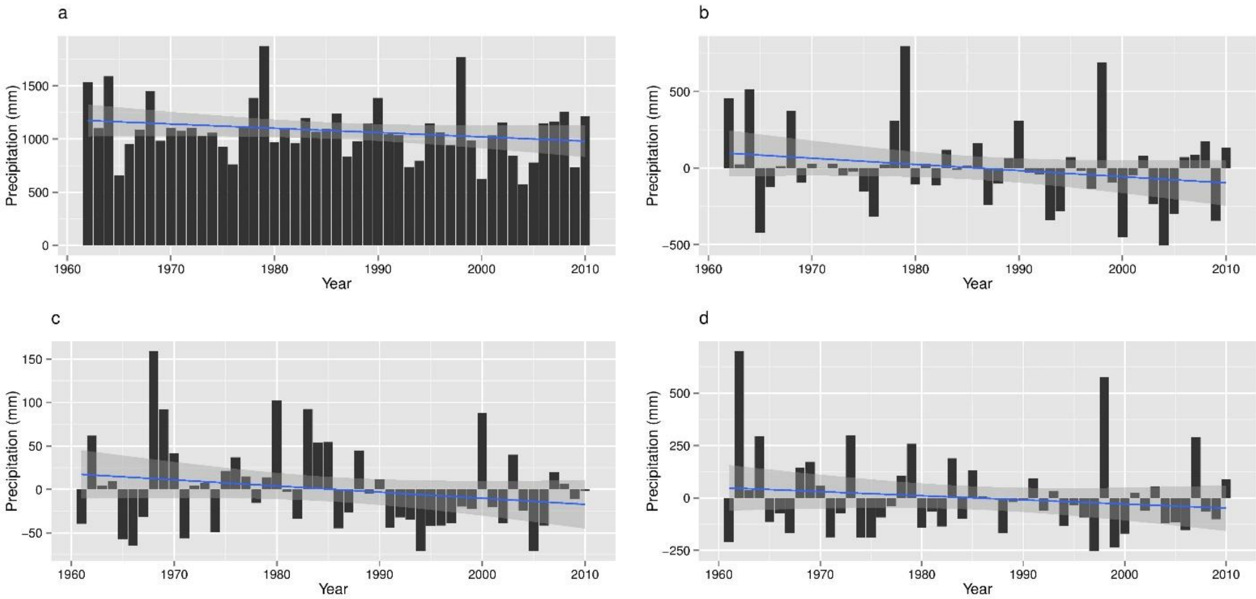

Fig. 2.4. Precipitation trends for the northern arabica growing regions of Tanzania. Trends are for the period 1960–2010 and represent the rainfall for the crop year (October–September) (a), anomalies for the crop year (b), anomalies for the dry season (June–September) (c) and anomalies for the flowering stage (October–February) (d). A linear regression line with an associated confidence band of 95% is fitted to each series.

2.3.2. 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. 2.2). 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. S2.1). 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 period1962–2003.

2.3.3. 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 2.1). 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 2.2).

Table 2.1

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

Source	T_{min}	T_{max}	T_{mean}	T_{minF}	T_{maxF}	T_{meanF}	T_{minR}	T_{maxR}	T_{meanR}
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***
NBSton	-0.649**	-0.310	-0.604**	-0.593**	-0.197	-0.548**	-0.636**	-0.272	-0.545**
NBSkgha^{-1}	-0.741***	-0.454**	-0.752***	-0.708***	-0.246	-0.661**	-0.694***	-0.459**	-0.692***
TCBton	-0.604**	-0.355	-0.650**	-0.545**	-0.179	-0.509**	-0.539**	-0.323	-0.559**
TCBkgha^{-1}	-0.585**	-0.422*	-0.682**	-0.557**	-0.169	-0.506**	-0.486**	-0.452*	-0.611**

* $P < 0.05$
** $P < 0.01$
*** $P < 10^{-6}$

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

Table 2.2

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
FAOkgha^{-1}	-0.024	0.196	-0.001	0.005	-0.073	-0.177	-0.308
NBSton	0.015	0.122	0.054	0.014	-0.028	0.200	-0.228
NBSkgha^{-1}	0.036	0.248	0.130	0.069	-0.076	0.019	-0.244
TCBton	-0.074	0.209	-0.108	-0.114	0.089	0.276	-0.473
TCBkgha^{-1}	-0.061	0.290	-0.04	-0.031	0.230	0.148	-0.464

* $P < 0.05$
** $P < 0.01$
*** $P < 10^{-6}$

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 every1°C increase in T_{min}, there is a loss of 137 ± 16.87 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 datamining, however, in order to derive a more biologically meaningful result, this relationship was investigated using non-linear (logistic) regression with the following equation:

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

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. 2.5). 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 approximately16.2°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.

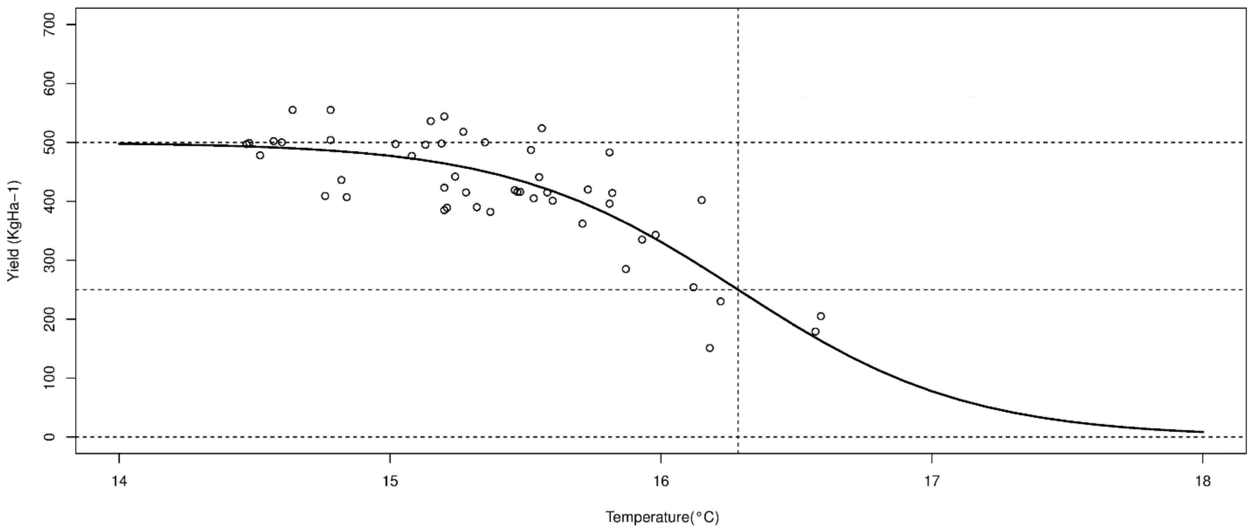

Fig. 2.5. Non-linear model of yield regressed by minimum temperature, extrapolated to 18°C.

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. 2.6). 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 ± 41 kg ha^{-1}(P = 8.45e-09) (Fig. 2.7). 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 ± 41 kg ha^{-1} (P = 8.45e-09) by 2060 and possible critical levels beyond that (Fig. 2.7).

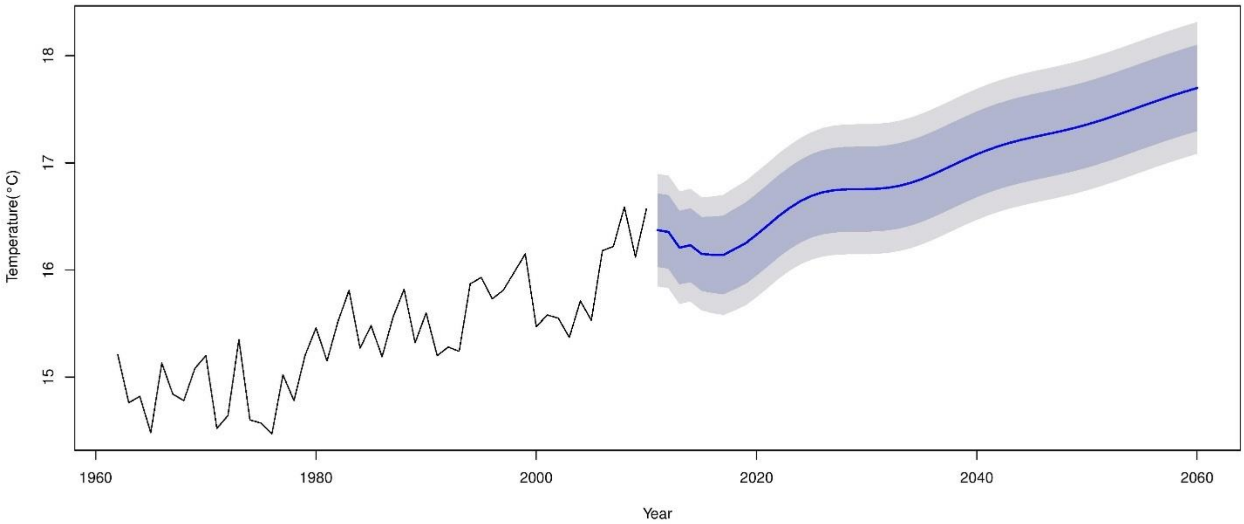

Fig. 2.6. ARIMA (5,1,2) model with forecasted minimum temperature for the period 1962–2060, with confidence vs. prediction intervals.

2.4. Discussion

2.4.1. Context and implications

These results suggest that the gradually increasing T_{min} in Tanzania may have a more pronounced impact on yield than stress from extreme minima (lowest annual temperatures) and maxima (highest annual temperatures), particularly over the longer term. The observed mean temperatures in the afromontane 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. 2.3). 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, a sigmoid curve was fitted to the data (Fig. 2.5). 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. 2.6). 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. 2.7). 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 ± 41 kg ha^{-1}(P = 8.45e-09) by the year 2060 (Fig. 2.7), as opposed to falling below 100 kg ha^{-1} (Fig. 2.5). When investigated linearly over the data period, yield loss per degree Celsius increase in T_{min} (137 ± 16.87 kg ha^{-1}, P = 1.80e-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; thus, it is suggested that the nonlinear and ARIMA functions are better representations of future change. With respect to coffee plant phenophases, these results suggest that yields are most strongly influenced by responses to atmospheric stimuli during the growing and flowering seasons.

Against expectations, 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 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 favourable growth for quality arabica (23°C) (Barros et al., 1997; Teixeira et al., 2013) (Fig. 2.3). 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.

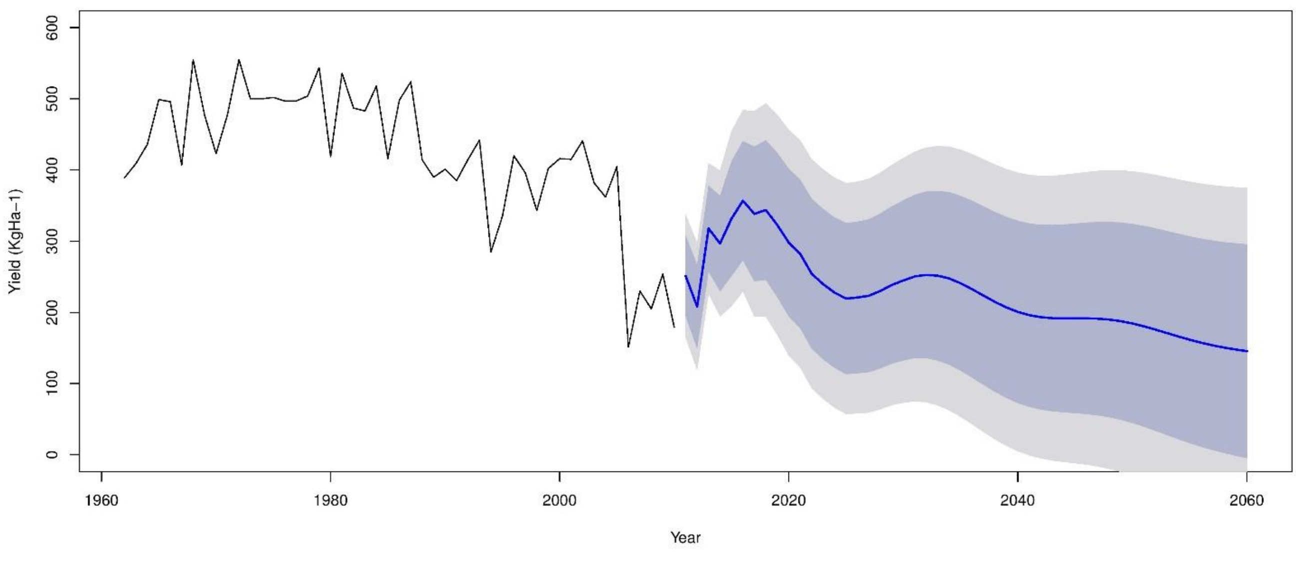

Fig. 2.7. ARIMA (5,1,5) model with forecasted yield based on extrapolated minimum temperatures for the period 1962–2060, with confidence vs. prediction intervals.

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). These 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).

2.4.2. Outlook

Mindful of the sensitive agroclimatic relationship described here, other major global *C. arabica* growing regions which face similar climate change scenarios are highlighted. 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} (delos 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 $T_{mean, min, max}$ 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 is this case in Tanzania, may thus not yet be clearly evident elsewhere, despite possibly being at risk.

2.5. Conclusion

Using several statistical analyses, the data show that gradually increasing T_{min} are significantly reducing arabica coffee yields in Tanzania. T_{min} have increased by 0.31°C/decade (P = 8.547e-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 = 1.80e-10). ARIMA model forecasts indicate 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 to145 ± 41 kg ha^{-1} (P = 8.45e-09) by the year 2060. However, considering the limitations of the linear regression and ARIMA models, the more applicable nonlinear 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 these 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. The 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 microclimate 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, attention is drawn to 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.

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CHAPTER 3

New insights regarding microclimatic effects on *Coffea arabica* yields: implications for climate change adaptation

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Abstract

Coffea arabica (C. arabica) is a temperature sensitive crop indicating declining yields under future climate projections. Understanding the effects of climate change on the plant under different cropping systems is a leading priority. Using a network of temperature and humidity data loggers in the coffee canopy microclimate, this paper demonstrates how increasing temperatures and vapour pressure deficit (VPD) are significant driving factors for coffee yields in Ngorongoro, Tanzania. The non-linear model indicates that attainable yields are high at mean temperatures (T_{mean}) of 16.5 to 18.5ºC. However, once the inflection point at 19ºC is reached, yields decline progressively toward a T_{mean} of 21ºC. Current growing-systems discourse is brought into question, as higher percentage shade systems tend to result in warmer night time temperatures in the meso- and microclimate, potentially inducing a negative impact on yield. The intrinsic relationship between these dynamics emphasizes the importance of selecting the correct type of shade for each climatic niche. Data show that precipitation during the flowering period has a small positive effect on yield, whereas total water (precipitation including irrigation) has no relationship to yield. Yield variability suggests that there are several other biotic and abiotic factors, as well as many complex interactions which influence coffee production. Nevertheless, these microclimatic results confirm previous findings which demonstrated for the first time that increasing minimum temperatures are largely responsible for declining coffee yields over a 49-year time series at national level in Tanzania.

Keywords: Agriculture; Minimum temperature; Microclimate; Agroforestry; Adaptation

3.1. Introduction

The year 2016 set a new record for the highest recorded global mean annual temperature since 1880; a powerful El Niño system helped drive temperatures past the previous record in 2015 (Mann et al., 2016; NOAA, 2017). Such recent dramatic warming has encouraged investigations into the impacts that climate change may have on various species, particularly those with economic implications, such as coffee (Mathur et al., 2012; Rippke et al., 2016). The coffee industry supports an estimated 125 million people worldwide and is a major GDP contributor for several East African countries (Pendergrast, 2010). Coffee is Tanzania's most important export crop, generating average export earnings of ~150 million USD per annum. Some of the finest quality coffee is grown within the forested rim of the Ngorongoro Crater and therefore attains considerable premiums worldwide (Tanzania Coffee Industry Development Strategy, 2012). However, recent studies have shown *C. arabica* to be severely vulnerable to climate change (Craparo et al., 2015; Läderach et al., 2016), with modelling projections depicting a reduction of suitable growing area globally (Bunn et al., 2014, 2015: Ovalle et al 2015), including complete extinction of wild populations in Ethiopia (Davis et al., 2012).

Supra-optimal temperatures and drought stress are shown to be major constraints to current and future coffee production (Gay et al., 2006; Bunn et al., 2015). Conversely, recent laboratory studies have shown that increases in CO_2 can mitigate the negative effect induced by supra-optimal temperatures on coffee, even when approaching substantially high temperatures of 42/34ºC (day/night) (Martins et al., 2016; Rodrigues et al., 2016). However, these studies use newer cultivars of *C. arabica* (e.g. cv. Icatu, IPR108), primarily developed for greater yields and resistance to pathogens. Due to repeated backcrossing with robusta and associated hybrids, these cultivars also have a greater adaptation potential to warmer temperatures compared to the more traditional varieties (Bourbon, Typica) grown throughout East Africa (Camargo, 2010; van der Vossen et al., 2015). Based on downscaled climate models, Tanzania is projected to experience a mean temperature increase of 2–4ºC by 2100 (IPCC, 2007; Läderach et al., 2012). Positive temperature departures of ~1°C or more may have strong implications for existing crop varieties (i.e. growth, diseases, yields etc). Importantly, temperature thresholds could be exceeded in highly niche-specific or temperature sensitive crops (Mathur et al., 2012). These thresholds may not necessarily be extreme minima or maxima, but rather the optimum growing temperature bracket. A growing body of work has advocated strong relationships between rapidly advancing minimum (night time) temperatures and the effects these have on tropical crops (Peng et al., 2004; Nagarajan et al., 2010; Luedeling, 2012; Bapuji Rao et al., 2014) and coffee specifically (Craparo et al., 2015). Mean temperatures rose by 1.42°C (P = 2.83e-14) in the arabica growing regions of Tanzania over the period 1960-2010 (Craparo et al., 2015). This trend was primarily driven by substantial increases in daily minima of 0.31°C/decade (P = 8.547e-12) (Craparo et al., 2015). These night time temperatures in turn were found to be the major limiting factor to yields, with a loss of 137 ± 16.87 $kgha^{-1}$ for every degree Celsius increase in minimum temperature (Craparo et al., 2015). Globally, minimum temperatures have increased about twice as fast as maximum temperatures (Vose et al., 2005; de los Milagros Skansi et al., 2013), and should this trend continue, will inevitably have profound impacts on the coffee sector worldwide.

The socioeconomic importance of *C. arabica* means that it features prominently in research focusing on how current and future climate [change] may impact production (Davis et al., 2012). However, several factors make understanding this relationship, challenging. A primary constraint is that smallholder production systems in East Africa are data poor. Therefore, the anticipated impact of climate change on coffee production is largely based on laboratory studies or suitability change maps using downscaled General Circulation Model (GCM) projections (e.g. Davis et al., 2012; Läderach et al., 2012; Bunn et al., 2015). Furthermore, the impact of climate change on *C. arabica* physiology is not consistent in each agroecological system (Bertrand, et al., 2016). Depending on the system, typical parameters such as shade, sunlight and altitude may either ameliorate or exacerbate the impact of climate change on the plant (Bertrand et al., 2016).

To this end, this paper aims to quantify the microclimatic and yield dynamics of *C. arabica in situ* over an altitudinal gradient in Tanzania. Importantly, the use of an altitudinal gradient (spatial scale) as a focus for plant-environment dynamics, enables the simulation of progressive climate change *in situ*, for a two-year period (2013-2015). A previous study investigating the impact of climate change on *C. arabica* using empirical data from Tanzania found a strong relationship between increasing minimum temperature and coffee yields over a 49-year period (Craparo et al., 2015). However, other factors such as aging plantations may have had collinearity with increasing temperatures, and thus skewed responses to yield. The objective of this study is to quantify the crop-climate relationship over a high spatial and temporal resolution in order to minimize the influence of various abiotic and biotic factors on yield. Temperature (altitudinal) gradients permit the relationship between temperatures and yield to be investigated while removing the factor of aging plantations as a determinant in yield loss over a time series. Understanding major current and future constraints for coffee production is fundamental for effective adaptation strategies and preservation of many specialty coffee growing areas worldwide. This paper highlights the major atmospheric constraints to coffee production in various agroecological systems, and in so doing, discusses important system dynamics such as temperature, shade and irrigation under climate change projections.

3.2. Materials and Methods

3.2.1. Study region and experimental design

This study took place on three commercial coffee estates situated on the south-eastern rim of the Ngorongoro Crater (Tanzania) over a period of two years (July 2013-August 2015) (Fig. 3.1). All three estates approximate similar age (40 years), grow complementary cultivars of coffee (Typica, Bourbon, Nyassa) and follow similar agricultural practices. A multiple-stem (two) system with capping has been adopted by all three estates. A total of 27 blocks (sub-sections of a coffee plantation) were selected, which cover an altitudinal gradient from 1377 to 1834 m a.s.l across the three estates. Blocks were chosen so that each estate offered the best possible representations of shade, ranging from full shade (100%) to full sun (0%) systems. Shade was calculated by firstly determining the average area of shade cast by each species of tree. The number of species per block was then used to obtain the shade percentage per block. The main shade trees planted include several species of *Albizia, Acacia, Croton, Cordia* and *Ficus*. While all estates practice stumping, none of the plants in the studied blocks were stumped during the two-year period.

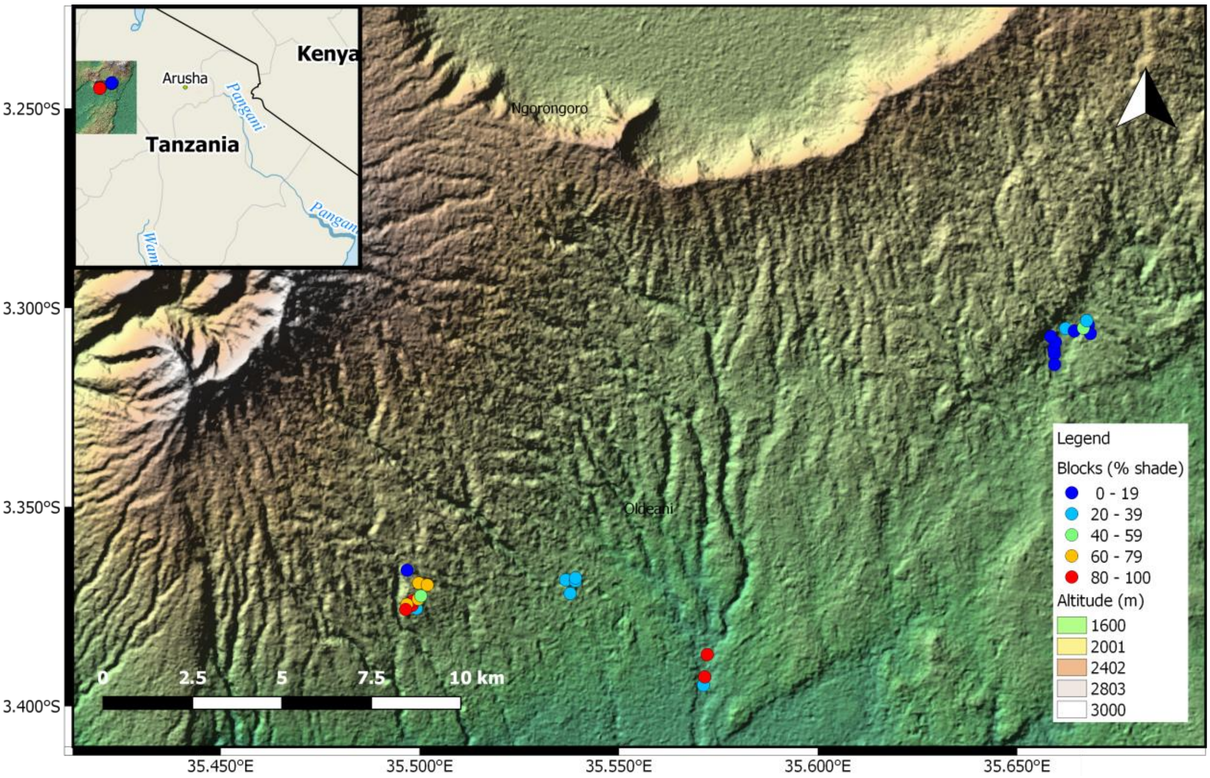

Fig. 3.1. Location of selected blocks of variable percentage shade, associated with altitude.

3.2.2. Microclimatic setup

A network of temperature and humidity data loggers were setup across the three estates with one logger in each block. Twelve calibrated TinyTag Plus 2 (Gemini TGP-4020) data loggers were used, which recorded temperatures from July 2013 to August 2015. The loggers have an external thermistor probe and measured temperature at 30 minute intervals with a ±0.02°C resolution. The probe was housed in a Stevenson-type screen which consisted of a 200mm long x 100mm wide white PVC tube covered in aluminium foil. The probe was suspended inside the tube so as not to make contact with sunlight or any of the tube sides, yet permitting free airflow. Loggers were installed inside the coffee plant canopy at ~1m above ground. The estates are located along the unfenced border of the Ngorongoro National Park and incorporate important bio-corridors for animals which pass through the coffee blocks. Hence, damage to trees and data logger equipment by wild animals and human interference was a logistical challenge. In order to mitigate such loss, 18 iButton Hygrochron (DS1923 Maxim) data loggers were installed, which measured temperature and humidity at 30 minute intervals from March 2014 to August 2015, with a ±0.5°C/±0.6% resolution. These small loggers may therefore be discretely concealed on the coffee stem at equal height in the canopy. The iButtons were housed in capsules which were open at the bottom and secured to the stem in the canopy facing the soil. In order to mitigate any contact with direct sunlight, the capsules were located under a further barrier of shade (constructed of tree bark) within the canopy. Three control blocks were established (with one TinyTag and one iButton installed next to one another) and measurements validated by comparing results. One control block was set up for each shade setting (i.e. 0% shade, ~50% shade, 100% shade).

Rainfall was measured daily with a standard rain gauge (Eijkelkamp, M4-1677e) at each estate. Two of the estates irrigate by drip (Estate 1 & 3, totaling 17 blocks), while the third (Estate 2, 13 blocks) relies only on rainfall. Irrigation scheduling is based on monthly precipitation, soil water data from tensiometers and precipitation forecasts. Irrigation generally commences at the start of the crop year (October/November) and continues as needed during the pinhead and fruit development period, which starts ~6 weeks after flowering and ends ~5 months later. The estates aim for 5mm/day during this period and if rain does not suffice, supplement with irrigation where possible. To gain a more accurate representation of water use, total water (W_T), which consists of the total rainfall for the crop year plus irrigated water, was established for each block.

3.2.3. Bioclimatic variables

To ensure the best representation of temperature experienced by the plant, mean minimum and mean maximum temperatures were used instead of absolute values. Minimum temperatures were calculated as the mean of temperatures between one hour after sunset (19:30h) and one hour after sunrise (07:30h). Maximum temperatures were calculated as the reciprocal of this. Thus, variables include; mean minimum (T_{night}), mean maximum (T_{day}) and mean (T_{mean}) temperatures for the crop year, which extends from October to September in Tanzania. Mean minimum (T_{nightF}), mean maximum (T_{dayF}) and mean (T_{meanF}) temperatures during flowering (October–February) and the mean minimum (T_{nightR}), mean maximum (T_{dayR}) and mean (T_{meanR}) temperatures during development/ripening (March–September) were also used. The diurnal temperature range (T_d) as well as vapour pressure deficit (VPD) were additionally calculated. Precipitation variables included total rainfall for the crop year (P_{yr}), total rainfall during the flowering period (P_F), total rainfall during the dry season (P_{dry}) prior to harvest (June–September), total rainfall during development/ripening (P_{dev}), and number of rain days during the short rain season (PD_{short}), long rain season (PD_{long}) and flowering period (PD_F). Minimum, maximum and mean relative humidity (RH_{min}, RH_{max}, RH_{mean}) were calculated with the same method used for temperatures, based on the mean diurnal and nocturnal humidity for each of the phenologically important stages. Yields (Y) are expressed as fresh cherry in $kgha^{-1}$, which may be converted to clean green bean with a general multiplication factor of 0.5. Once the coffee had been harvested, the cherries were weighed by the estate managers on an industrial scale.

3.2.4. Statistical Analyses

To extend the dataset, a daily autoregressive integrated moving average (ARIMA) model was built to backcast the temperature variables, hence including the entire crop year of 2013. Autocorrelation functions (ACF) and partial autocorrelation functions (PACF) were used to identify models. The model with lowest Bayesian information criterion (BIC), which was statistically significant, was then considered a good fit model. Pearson's correlation coefficient (r) was used to determine significant relationships between the bioclimatic variables and yield. All-subsets regression was used to select parameters for each model. Diagnostic plots and component residual plots were used to check for model fit and normality of the residuals in the linear regression. To provide a more accurate description of biological growth functions, a non-linear regression with a logistic function was built. 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 3.3.0.

3.3. Results

3.3.1. Microclimatic dynamics

Annual T_{mean} ranged from 17.6°C to 21.1°C across all blocks over the entire recording period, with monthly T_{mean} illustrated in Fig. 3.2a. Annual T_{day} fluctuated from 20°C to 24.4°C, with monthly T_{day} represented in Fig. 3.2b**.** At the lower boundary, annual T_{night} ranged from 14.9°C to 18.3°C, with monthly T_{night} illustrated in Fig. 3.2c. Despite some distance between the three estates (~25km) and an altitudinal range of ~450m, microclimatic temperatures in each block follow precisely similar trends. The control sites with two different temperature sensors highlight differences between vertical and horizontal heat convection (Fig. 3.3.). Temperature differences between sensors are largely negligible, particularly for T_{night} and microclimate settings where the canopy is partly or fully shaded (Fig. 3.3a). However, where blocks are in full sun, iButtons record a slightly higher (on average by 3ºC) T_{day} even though both sensors remain in the shade (Fig. 3.3b). T_{night} is directly proportional to shade, yet there is no significant correlation to T_{day} (Table 3.1). A 10% increase in canopy cover raised T_{night} by a factor of

0.10°C (P=0.0003). T_{night} of a block that has 100% canopy cover would therefore be approximately 1°C warmer than one without a canopy.

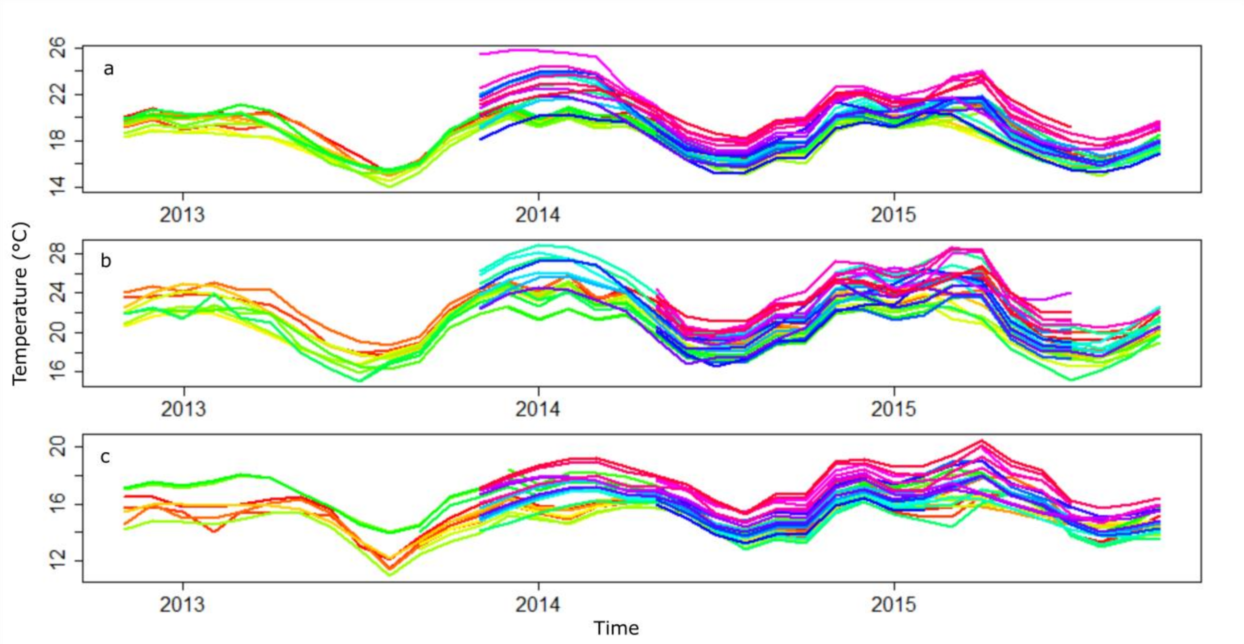

Fig. 3.2. Mean monthly air temperatures for all blocks. Temperatures include T_{mean} (a), T_{day} (b) and T_{night} (c). Different line colours represent different blocks. TinyTag data starting in July 2013 were backcast to October 2012 and iButton data starting March 2014 were backcast to October 2013.

Average annual VPD ranges from 0.37 kPa to 0.57 kPa, depending on the block. Correlation to temperature, suggests that this variability in VPD is primarily driven by micrometeorological temperature variability, rather than larger meso- or macroclimatic phenomena which alter humidity. Mean annual T_d ranged from 3.3ºC to 9ºC between blocks. T_d is strongly correlated to shade, where a 10% increase in shade results in a reduction of -0.2ºC in diurnal temperature (Table 3.1, P= 1.13e-07).

No significant correlation between precipitation and altitude is found, most likely given that the majority of blocks are within a narrow altitudinal range (457m) on the crater rim, and only a few situated in the valleys below. However, if the lowest and highest blocks are considered, there is a difference of approximately 400mm in precipitation. P_{yr} ranges from 515mm in the lowest blocks, to 1175mm in the upper altitude blocks. An average of 818mm is recorded for all blocks over the two years. Therefore, the actual water supplied or W_T, ranges from 647mm (unirrigated at altitude: 1780m) to 1486mm, which covers irrigated blocks in the 1500 – 1687m a.s.l. range.

A negative correlation between P_{yr} and T_{night} (r = -0.47) is recorded, which becomes stronger during the development/dry season. However, there is no significant relationship between precipitation and T_{day}. Given that several of the blocks are irrigated, this permits a better understanding of the collinearity between these two variables and yields. In line with the fundamental relationship between RH and temperature, there is a strong negative correlation between RH_{min} and T_{day}; where a 3.8% RH_{min} loss is recorded for every degree Celsius rise in T_{day} (2.12e-10). Likewise, the RH_{max} increases by 1.57% for every degree Celsius drop in T_{night} (P=3.48e-07).

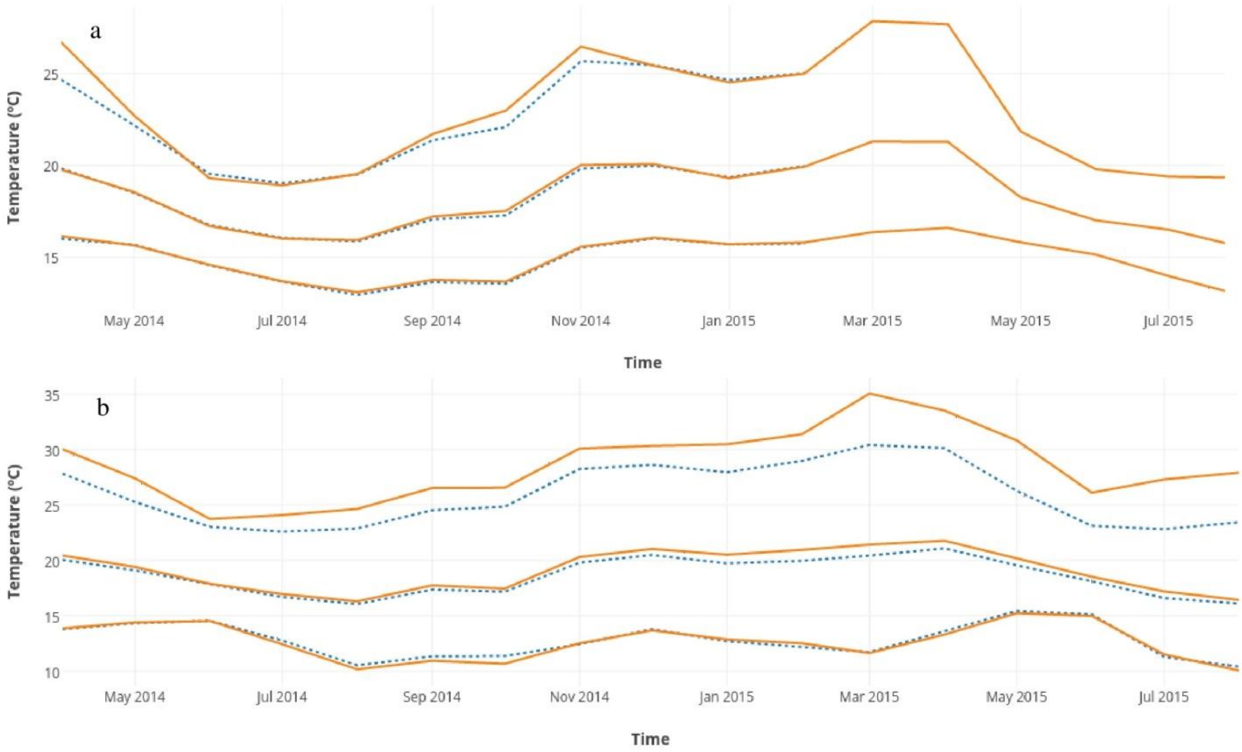

Fig. 3.3. T_{mean}, T_{day} and T_{night} trends for TinyTag and iButton sensor control sites. Graph (a) represents a block in 100% shade; graph (b) represents a block in full sun. Orange lines are temperatures from iButtons and blue dashed lines from TinyTag loggers.

3.3.2. Yields

Yields are expressed as fresh cherry in $kgha^{-1}$ and range from a minimum of 28 to 2492 $kgha^{-1}$ over the three harvest periods, with an average of 949 $kgha^{-1}$ (Fig. 3.4). However, large standard deviations in yields occur between blocks as well as within the same block in consecutive years. While *C. arabica* has a biennial nature, the canopy structure and pruning techniques followed are designed to minimize differences between a substantial crop in a given year and a lower harvest the following year (Lambot and Bouharmont, 2009). Interestingly, the estate which does not irrigate (Estate 2) has a very similar coefficient of variation in interannual yields (32%) to that of one of the estates that does irrigate (33%). More commonly, a greater coefficient of variation in yields is recorded if the plant is reliant solely on precipitation (Carr, 2001). In contrast, the other estate that irrigates has an average coefficient of variation of 50% for all blocks between years.

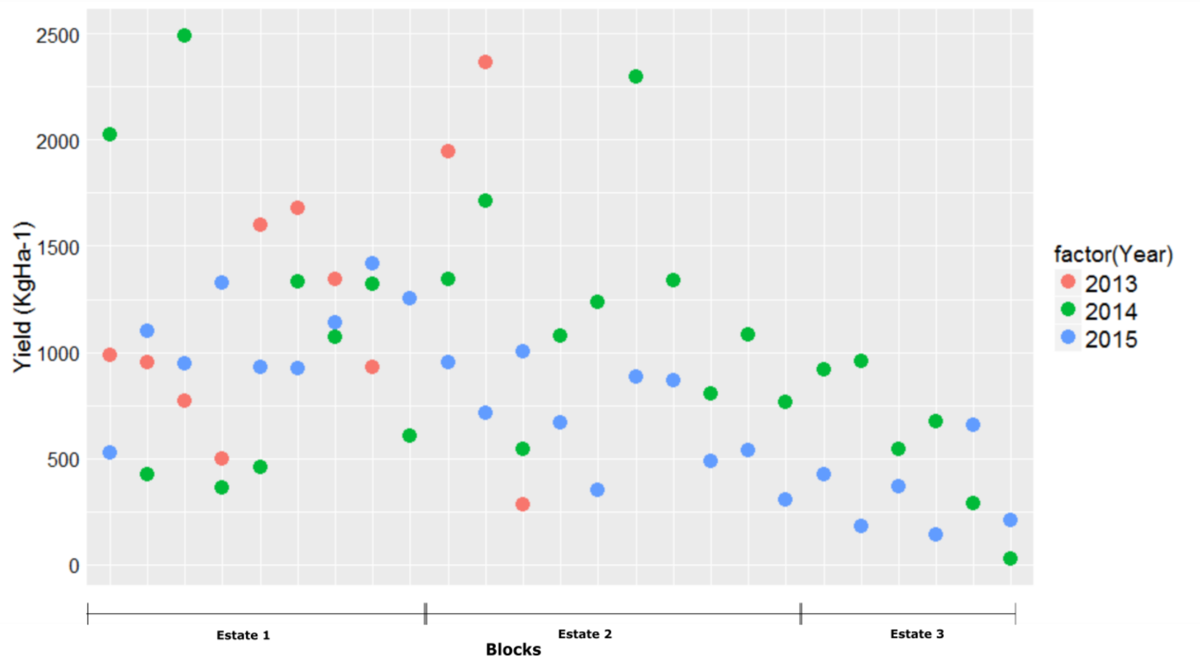

Fig. 3.4. Yields per block for the three harvest seasons (2013, 2014 & 2015). Estate 1 and 3 are irrigated.

3.3.3. Microclimatic influence on yields

Out of all agrometeorological parameters, temperatures during the principle phenological phases have the greatest influence on yields (Table 3.1). T_{dayR} accounts for the highest variance (R^2=0.25) and when investigated linearly, there is a loss of 200 ± 53 $kgha^{-1}$ for every degree Celsius increase in T_{dayR} ($P=<10^{-6}$). Following in a similar manner, increases in T_{night} result in substantial losses in yield. Fundamentally linked to this, VPD has a strong negative correlation to coffee production, where an increase of 0.1 kPa results in a loss of 367 $kgha^{-1}$ (P=0.018, Table 3.1). However, it should be noted that this model has a much lower number of degrees of freedom. T_{mean}, T_{meanF} and T_{meanR} are the next most influential climatic variables. While mean temperatures in several of the phenologically important stages have significant correlations to yield, it is imperative to determine when stress is greatest; hence more emphasis is placed on temperature boundaries (T_{night} & T_{day}). Contrary to current coffee physiology research (Ramírez et al., 2010), T_d does not feature as a major yield constraint in this environment. P_F and P_{yr} both have a small positive effect on yields, with an increase of 40.6 kg ha^{-1} for every 10mm increase in rainfall (P=0.001). However, these relationships should be used with caution as the majority of blocks (16) are supplemented with irrigation. Accordingly, encompassing precipitation and irrigation, W_T has no relationship to yields (Table 3.2). With regards to the collinearity between temperatures and rainfall, these findings suggest that it is not an increase in rainfall (and consequential decrease in temperature) which is correlated with yields, but rather the effect of actual temperature itself. Likewise, the number of rainfall days during important phenological phases does not seem to influence yields.

Table 3.1

Pearson correlation values for yield (Y) and temperature variables. *Mean minimum (T_{night}), mean maximum (T_{day}) and mean (T_{mean}) temperatures for the crop year, mean minimum (T_{nightF}), mean maximum (T_{dayF}) and mean (T_{meanF}) temperatures during flowering, mean minimum (T_{nightR}), mean maximum (T_{dayR}) and mean (T_{meanR}) temperatures during development/ripening, diurnal temperature range (T_d), vapour pressure deficit (VPD)*

	T_{night}	T_{day}	T_{mean}	T_{nightF}	T_{dayF}	T_{meanF}	T_{nightR}	T_{dayR}	T_{meanR}	T_d	VPD
Y	-0.398**	-0.294*	-0.446**	-0.303*	-0.364**	-0.488***	-0.231	-0.503***	-0.553***	-0.08	-0.502**
Shade	0.473***	-0.209	0.028	0.536 ***	-0.275*	0.093	0.192	-0.258	0.094	-0.648***	-0.05

* P < 0.05 ** P < 0.01 ***P < 10-6

Table 3.2

Pearson correlation values for yield, precipitation and water variables. *Total water (W_T), total rainfall for the crop year (P_{yr}), flowering period (P_F), dry season (P_{dry}), development/ripening (P_{dev}), number of rain days during the short rain season (PD_{short}), the long rain season (PD_{long}) and the flowering period (PD_F)*

	W_T	P_{yr}	P_f	P_{dry}	P_{dev}	PD_{short}	PD_{long}	PD_f
Y	0.079	0.298*	0.424**	0.237	0.263*	-0.249	-0.055	-0.187

* P < 0.05 ** P < 0.01 ***P < 10-6

According to all subsets regression, adding a second predictor variable introduces P_{yr} and T_{night}. However, the addition of a second and third (VPD & T_{day}) predictor variable does not contribute to any further explanation of variance (R^2=0.19) and the unnecessary predictors add noise to the estimation of other quantities, so were therefore omitted. Based on results of the component residual plot and in order to derive a more biologically meaningful result, a sigmoid function was fitted to the data (Fig. 3.5) using the following equation:

$$kgha^{-1} = \frac{2600}{\{1 + \exp[-(6.6175 \pm -0.4667 \times T_{night})]\}}$$

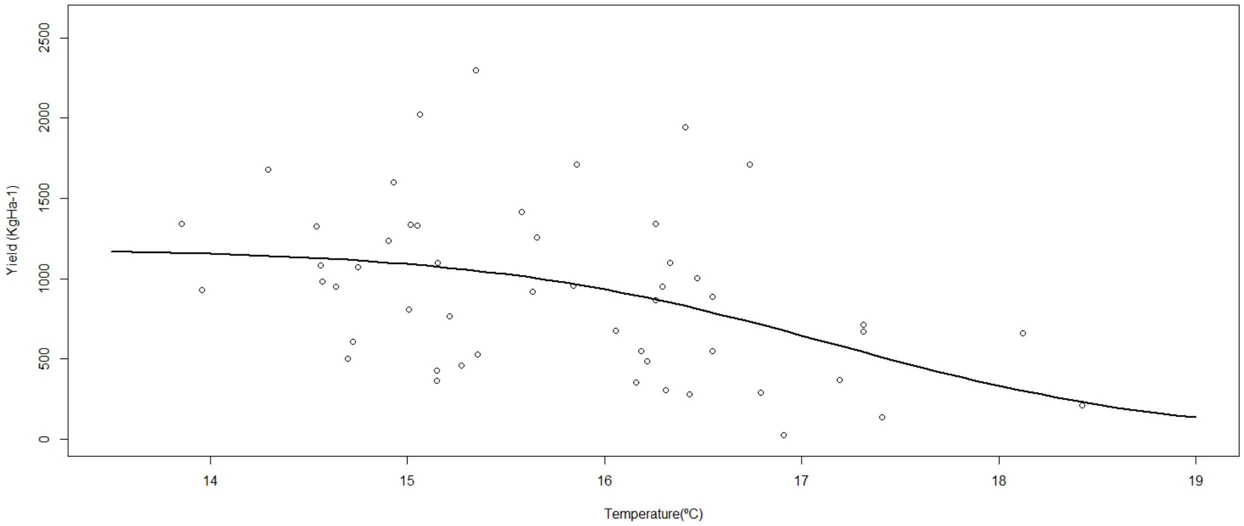

Fig. 3.5. Non-linear model of yield regressed by T_{night}.

This function best represents the typical biological growth pattern, whereby the plant excels at a comfortable mean T_{night} range of 13.5 to 16.5ºC. However, as the 16.5ºC mark is breached, yields decline substantially (Fig. 3.5). The model suggests that once such temperatures approach 20ºC, yields would become critically low, yet limited cultivation might still be possible. Considering T_{mean}, a non-linear function was fitted to these data with the following equation:

$$kgha^{-1} = \frac{2600}{\{1 + \exp[-(14.4311 \pm -0.8285 \times T_{mean})]\}}$$

The model suggests attainable yields are high between 16.5 and 18.5ºC (Fig. 3.6). Yet, once temperatures surpass the 19°C inflection point, yields decline rapidly and reach substantial lows at a T_{mean} of 20ºC.

3.4. Discussion

3.4.1. Microclimatic influence on C. arabica yields

With a high spatio-temporally resolved analysis of 28 coffee blocks, these results support recent courser resolution (national scale) findings, which suggest that increasing temperatures and specifically minimum temperatures, have the greatest impact on *C. arabica* yields (Craparo et al., 2015). Importantly, this study enabled several variables such as agronomic techniques, plant varieties and aging plantations to be held constant. Majority of block canopy temperatures remained within the suggested optimal T_{mean} bracket of 18-21ºC (Alègre, 1959). However, several blocks experienced a mean monthly T_{night} of >=18ºC, thereby pushing the T_{mean} to the upper limit of the optimal growth bracket. The nonlinear model illustrates how mean T_{night} between 13.5ºC and 16.5ºC favour high yields (Fig. 3.5). Yet, as minimum temperatures surpass the 16.5ºC mark, yields decline substantially. This is in accordance with the sigmoid curve used to model macroscale data in Tanzania, such that the maximum rate of yield decline is reached at the inflection point at approximately 16.2ºC (Craparo et al., 2015). The function then progresses with decreasing deceleration toward a mean T_{night} of 19ºC, whereupon yields are largely reduced. Numerous abiotic and biotic factors such as pests and diseases, soil moisture and quality, as well as micro and macronutrients, influence the plant's physiology and consequent production. While this study attempted to hold as many variables as possible constant, these blocks are all part of working estates with other heterogeneous dynamics. It is therefore proposed that the observed high variability between yields in the "suitable" T_{night} range (13.5-16.5ºC) is at least in part owing to the effects of other stimuli and inputs such as pests and diseases, variety in fertilizers and their application, and soil properties, to name a few.

The stated optimum mean temperature bracket for *C. arabica* is 18-21°C (Alègre, 1959). However, these data indicate that there is a breakpoint at a T_{mean} of ~18.7ºC for these varieties (Fig. 3.6). Majority of the points fall into a cluster around 17.5-18.5ºC, where attainable yields are high. An earlier study by Silva et al. (2004) found a similarly strong negative relationship between increasing temperatures and branch growth. Furthermore, it has been shown that where temperature is ~2.5°C higher than the upper limit for *C. arabica* cultivation, there is increased nitrogen content in the bean, and also a reduction in the bean density and sensory quality of the beverages (Da Silva et al., 2005; Vaast et al., 2006; Joët et al. 2010). More recently, Rodrigues et al. (2016) found that low temperatures had resulted in unaltered fluorescence parameter values (indicating a high functional stability) as well as a higher number of nodes, thereby inducing a potential positive impact on yield. As evident from these data, the reason for this may be associated with the effect of night time temperatures on flowering. In equatorial areas where the photoperiod is less than 13 hours, coffee flower induction is related to temperature changes (day / night) and the potential synergistic effect with water deficit (Ramirez et al., 2010; Jung et al., 2016). Ramirez et al. (2010) show how "thermal shock" with a diurnal temperature range in excess of 10ºC is required by the plant to break dormancy. Given that the diurnal temperature range rarely exceeds 9ºC in our study, particularly during flowering, this may explain the lack of relationship between yields and diurnal temperature. Early studies by Went (1957) and Mes (1957) discovered that warmer night time temperatures (26ºC) with stable days (23ºC) generally produced many flower buds, however these buds subsequently turned into star flowers or dried up. In contrast, a maximum day-temperature of 23ºC with corresponding night temperature of 17ºC produced many flower buds which later developed normally into fruits. Hence, the effects from increasing temperatures at the lower end of the spectrum may explain the diminishing yields observed above 19ºC on the nonlinear model of T_{mean} (Fig. 3.6).

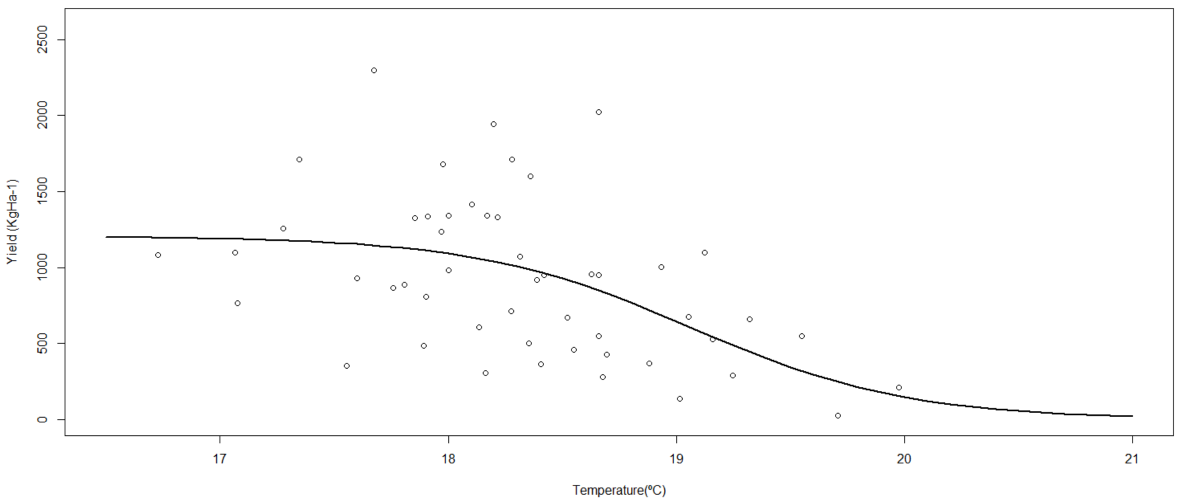

Fig. 3.6. Non-linear model of yield regressed by mean temperature, extrapolated to 21ºC.

Rainfall plays a fundamental role not only in coffee physiology, but also phenology (Rodrigues et al., 2016). Notably, actual water supplied to the crop (W_T) had no relationship to yields, while P_{fl} and P_{yr} had a small positive effect. The stated optimum annual precipitation requirement for coffee is 1200 – 1800mm (Alègre, 1959). The unirrigated blocks in this study, fall below this range with an average of 775mm for the three studied years. While there is a positive correlation between yields, P_{fl} and P_{yr}, additional irrigation (W_T) does not seem to contribute positively to coffee production. Lack of correlation between these variables does not necessarily suggest they are unrelated, but rather that microenvironment compensates for water deficit within the system. More specifically, water requirements typically depend on soil retention properties, root structure, cultivar, canopy microclimate and cultivation practices (DaMatta and Ramalho, 2006). Physiologically speaking, drought only occurs when potential evapotranspiration exceeds water supply. Therefore, although several blocks in this study fell below the optimal lower water limit (1200mm) ", sound agronomic practices and conducive agroecological systems such as those mentioned above, may positively assist the plant in coping with reduced water supply.

3.4.2. Microclimate dynamics and climate smart agriculture

Coffee plant performance in terms of growth, biomass accumulation and productivity relies on acclimation capability to environmental changes (Ramalho et al., 2014). This capability subsequently changes depending on the abiotic and biotic structure of each particular ecological niche, as well as the phenotypic plasticity of the plant (Bertrand et al., 2016). It is therefore argued that common notions of what is beneficial or detrimental to a coffee plant, may not be applicable in every environment and should thus be used with caution.

Results from this microclimatic study indicate that the values of several environmental parameters, including optimum growing temperatures, water requirements and shade, are atypical. The longstanding accepted optimum mean growing temperatures for *C. arabica* are 18-21ºC, as suggested by Thurber (1881) and later confirmed by Alègre (1959). However, these data suggest that mean temperatures with an upper limit of 18.5 or 19ºC would be more appropriate, particularly for the "traditional" varieties (e.g. Typica, Bourbon) grown in northern Tanzania (Fig. 3.6). In fact, results accord with Dahlgren's (1938, 12) proposition that cultivation is best at a "mean temperature of 60° to 72° Fahrenheit (16°-22°C), or, still better, approaching as closely as possible to 65° Fahr. (18°C)". Although it is a small temperature variation in optimal growing condition, a boundary limit of 19ºC as opposed to 21ºC is a fundamental difference to the suitability of *C. arabica* areas under current and future climate change projections (Bunn et al., 2015). Attention should therefore be drawn to critical *C. arabica* producing areas in Costa Rica, Colombia and Ethiopia where similar trends of rapidly advancing T_{night} are being recorded, which may thus force T_{mean} to undesirable limits (Quintana-gomez, 1999; Pounds et al., 2006; de los Milagros Skansi et al., 2013; Mekasha et al., 2014).

It should be noted that the temperatures used in this study are the mean day and night, as opposed to absolute day or night temperatures and therefore may be more conservative than those found in other (earlier) studies.

Several benefits of shading include the recycling of nutrients and soil organic matter sustenance, improved coffee quality, increased biodiversity and increased livelihood security (cash crops from fruits or timber) (Vaast et al., 2006; Jha and Dick, 2010; Cerda et al., 2017). These are particularly beneficial in marginal coffee growing areas (Van Kanten & Vaast, 2006; Vaast et al., 2007; Lin, 2007). Substantial shade (~100%) within the lowest altitude blocks at 1380m a.s.l, reduced T_{day} to levels of 1-2ºC lower than corresponding blocks at 1550m a.s.l with ~20% shade. This phenomenon has been observed in many coffee and cocoa agroforestry systems (Vaast et al., 2015). In terms of climate change and agroforestry, this produced a positive change within the system by buffering maximum temperatures (Lin, 2007). Shade trees would possibly have provided several other benefits, such as positively altering the water balance in the coffee system by reducing evaporative demand from soil and leaf transpiration (Carvalho, et al., 2016). However, despite these beneficial attributes, shade also created an unintended "greenhouse effect" by raising T_{night} to within the lower limit of the optimal temperature bracket. Furthermore, the presence of shade also reduced the diurnal temperature range, but did not have any effect on VPD. The majority of shade trees within this particular block were not short trees with dense canopies, but rather consisted of *Grevillea robusta,* which reach 20m in height and have a relatively sparse canopy (Dharani, 2011). In addition to the influence of shade on the microclimate, increased shading has been linked to reduced flowering intensity and therefore may be acting synergistically with increased T_{night} on yields. Where coffee is under heavy shade (>70%), flowering intensity may be reduced to 10% of the full sun potential, resulting in a final loss in yield of over 50% (Vaast et al., 2008).

The effects of shading on temperatures were less pronounced in blocks which were situated at the highest altitude of 1700-1900m a.s.l. Results were typically more varied between full shade and full sun blocks, where an increase/decrease of shade did not necessarily reduce/increase temperatures in each case. The dissociation between these variables at higher altitudes and effect on VPD, is likely a result of geographic scale as well as the variability in shade leaf cover throughout the year. More specifically, the greater surrounding area/blocks would induce meso- and macroclimatic forcing which in turn alter microclimatic dynamics. A trade-off analysis would thus be necessary to determine whether lower altitude sites may have greater benefit with reduced shade. Climate smart systems at these altitudes may mean a sparser canopy which would permit terrestrial radiation to escape at night and reduce T_{night}, while still somewhat reducing T_{day} (Lin, 2007). This may be achieved by periodic pruning of shade trees, as is commonly practiced in Central America particularly with Erythrina poeppigiana in Costa Rica and Inga spp. in Nicaragua and Guatemala (van Kanten and Vaast, 2006). Pruning of shade trees at strategic times, such as a few weeks before flower induction is triggered, has a strong positive impact on flowering intensities (Vaast et al., 2008). To compensate projected future warming, careful species selection and management of shade trees (pruning) is likely to become essential in order to achieve optimal coffee producing microenvironments and lessen the impacts of increasing temperatures (Cerda et al., 2017).

3.5. Conclusion

Using key microclimatic data from coffee estates on the Ngorongoro Crater rim, these results illustrate that increasing temperatures and VPD have a potentially detrimental effect on coffee production. Importantly, even with substantial inputs, the upper limits of the optimal temperature bracket of 20-21ºC consistently produces lower *C. arabica* yields than plants grown in lower temperatures. Increased irrigation above 1000mm per annum, did not appear to add any further value to coffee production. It is acknowledged that several other biotic and abiotic factors such as pests and diseases, variety and application of fertilizers, as well as soil properties, influence production, which may in turn explain the high variability between block yields. The altitudinal microclimatic data, simulating progressive climate change, enabled the determination of relationships between microclimate and yield, while holding several factors constant (aging plantations, agronomy techniques and plant varieties). In so doing, key uncertainties arising from previous macro-scale (country scale) investigations (e.g. Craparo et al., 2015), have now been addressed. These results substantiate the fact that increasing T_{night} is responsible for significant yield declines. Findings are based on production values from commercial estates with good agricultural technology and access to inputs. Despite this, farmers struggle to achieve yields above 500 $kgha^{-1}$ at a T_{mean} of 20ºC. A smallholder farmer with far fewer resources and access to inputs may therefore operate at an even greater deficit with increasing temperatures. These results emphasize the importance of scientific investigations at a site-specific scale when: a) attempting to establish and project responses to climate change, and b) determine appropriate adaptation practices. Furthermore, the design structure of the agroforestry system, particularly in relation to surrounding geography and mesoclimate, should be taken into consideration to maximise suitable microclimates for *C. arabica*.

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CHAPTER 4

Microclimatic impacts on *Coffea arabica* phenology under a climate warming scenario in Tanzania

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Abstract

Studies have demonstrated that plant phenophases (e.g. budburst, flowering, ripening) are occurring increasingly earlier in the season and are intrinsically linked to rising temperatures and changing precipitation patterns. Despite much interest that climate change impacts have on coffee (*C. arabica*), relatively little is known about the driving factors determining its phenophases. Using high resolution microclimatic data, this study provides initial insights on how climate change is impacting *C. arabica* phenophases in Tanzania. Principally, warming temperatures are shown to have a superseding effect on the ripening of coffee and subsequent timing of harvest. In particular, mean night time temperature (T_{night}) permits accurate prediction of the start of the harvest season. The linear regression model is statistically robust ($R^{2=}0.57$, $P<.001$) and indicates that for every 1°C increase in T_{night}, harvest start dates advance by 15.4 days. To this end, earlier bean ripening may have negative implications for yield quality and quantity due to the plant's shortened development period. Using this T_{night} variable will thus not only allow farmers to more accurately predict their harvest start date, but also assist with adaptation to climate change. It is proposed that climate-warming adaptation strategies focus on reducing the rapidly advancing T_{night}, and so challenge the common perception that shade trees are a key solution for climate change adaptation in coffee.

Keywords

Harvest phenology; night time temperature; climate change; *Coffea arabica*

4.1. Introduction

The timing of biological events, particularly in plants, is strongly controlled by climate. Hence plants are optimal organisms for studying climatic change as they are sessile and must consequently endure all weather conditions to which they are exposed *in situ* (Gordo and Sanz, 2010). The plants' phenotypic plasticity is what most climate-phenology studies are based on. Temperature is now widely regarded as the most consistent and dominant controller in the timing of flowering phenology, particularly for temperate plants and ecosystems (e.g. Grab and Craparo, 2011; Fitchett et al., 2014; Shen et al., 2014; Zhang et al., 2015; Crabbe et al., 2016). Optimal temperature ranges allow for correct functioning of the plants' metabolic processes and photochemistry. For many species, it also directly controls the dynamics of plant development through the process of chilling and forcing requirements during dormancy (Luedeling et al., 2013). Other environmental parameters such as photoperiod, precipitation and soil moisture may contribute to phenological processes; however, these parameters are largely considered subordinate to temperature and usually interact in a complex dynamical manner (Gordo and Sanz, 2010).

Africa comprises more coffee producing countries (25) than any other continent. There are an estimated 12 million coffee farmers in total, compared to a mere ~4 million in Asia and Oceania, which is the next largest consortium of farmers (ICO, 2015). Coffee (*C. arabica*) accounts for ~5% of Tanzania's total exports by value and provides direct economic support to ~450 000 smallholder farmers (USDA, 2016). Several highland areas in Tanzania produce specialty-grade coffee and therefore obtain considerable premiums worldwide (Tanzania Coffee Industry Development Strategy, 2012). Recently, the future of coffee production and security of smallholder farmer livelihoods has gained immediate attention as several studies have demonstrated the vulnerability of *C. arabica* to climate change (Davis et al., 2012; Bunn et al., 2014, 2015; Craparo et al., 2015). Supra-optimal temperatures and drought stress are shown to be major constraints to current and future coffee production (Gay et al., 2006; Bunn et al., 2015). Since the large push toward full sun systems in the early 1990's, there has been a strong focus on shading and agroforestry as a measure of crop protection against changing climate (Lin, 2010), particularly under sub-optimal conditions (van Kanten & Vaast, 2006). However, rising night time temperatures from increased shading and potential consequent effects on coffee crop physiology and production, have not yet been completely addressed (Craparo et al., in review). Studies have shown that rapidly advancing minimum or night time temperatures have a detrimental effect on coffee yields at local (Craparo et al., in review) and national scales (Craparo et al., 2015), as is also the case for several other tropical crops (Peng et al., 2004; Nagarajan et al., 2010; Luedeling, 2012; Bapuji Rao et al., 2014). A recent pioneering study by Jung et al. (2016) revealed how plant phytochromes (red light receptors) actually function as thermoreceptors at night, providing a molecular explanation as to why night time temperatures are key drivers in the production of *C. arabica*. The molecular change is directly proportional to temperature; therefore, the warmer it is at night, the faster plant growth is stimulated. Despite considerable current scientific attention on how climate change is impacting the coffee sector, an ongoing knowledge gap is how climate change parameters may be affecting coffee phenology.

The majority of coffee phenology studies have modelled its flowering and ripening. The most commonly used parameter to predict optimal harvest time is days after flowering (DAF), whereby under optimal climatic conditions, *C. arabica* fruits reach maturity at ~32 weeks after anthesis (Sondahl and Sharp, 1979; Pezzopane et al., 2012). However, several environmental and genetic parameters influence plant physiology, resulting in phenotypic plasticity (e.g.Silva et al., 2004; Da Silva et al., 2005; Ramirez et al., 2010; Rodrigues et al., 2016). Camargo and Camargo (2001) present a model to predict the beginning of the main flowering period in Brazil, where the sum of potential evapotranspiration (ET_p) needs to reach 350mm, together with the occurrence of 10mm of rainfall, to achieve flowering. Zacharias et al. (2008) subsequently refined the parameters to 335 ET_p and a minimum of 7mm of rainfall for an improved model prediction. Using a base temperature threshold of 10.5ºC, Pezzopane et al. (2008) developed different heat sum models for the Mundo Novo IAC 376–4 cultivar and suggested that a minimum of 2,887 accumulated growing degree-days (GDD) is required for plants to complete the flowering to harvest period (taken as the weighted average date of harvest for all experimental blocks). More recently, it has been found that the highest rate of sucrose accumulation in the cherry occurs at transition from the cane-green to cherry phenological stage, and that the GDD and reference evapotranspiration (ET_0) variables are superior to the DAF for model prediction (Pezzopane et al., 2012).

Given considerable recent work (e.g. Bunn et al., 2014, 2015; Craparo et al., 2015; Läderach et al., 2016; Martins et al., 2016), there is now a much better understanding of how current and future climate change may impact *C. arabica* yields or its relative environmental suitability. However, the extent to which climate change affects coffee phenology, remains uncertain. To this end, using a high resolution spatio-temporal dataset, this study aims to quantify the primary meteorological variables that drive coffee harvest phenophases in the Ngorongoro coffee growing region of Tanzania. Based on these relationships, potential impacts of climate change on coffee phenology to the year 2060 are then quantified using long-term climatic forecasts for this region, as modelled by Craparo et al. (2015).

4.2. Materials and Methods

4.2.1. Study region and experimental design

The field study took place on two commercial coffee estates situated on the south-eastern rim of Ngorongoro Crater (Tanzania) over a period of two years (July 2013-August 2015) (Fig. 4.1). Both estates approximate similar age (30-50 years) and follow comparable agricultural practices. In addition, both estates grow the same variety of cultivars including Typica, Bourbon and Kent. A total of 22 blocks (sub-sections of a coffee plantation) were selected; these range in altitude from 1551 m to 1834 m across the two estates. One estate irrigates by drip, while the second relies solely on rainfall. Blocks were selected to achieve the best possible representation of shade; ranging from full shade (100%) to full sun (0%) systems. The main shade trees planted include several species of *Albizia*, *Acacia*, *Croton*, *Cordia and Ficus*. Percentage shade was calculated manually by measuring the average area of shade cast by each species of tree. Shade percentage per block was then determined by the number of tree species per block and the area of the block. Blocks were chosen with coffee plants of similar allometry including stems of the same height with roughly equivalent diameters.

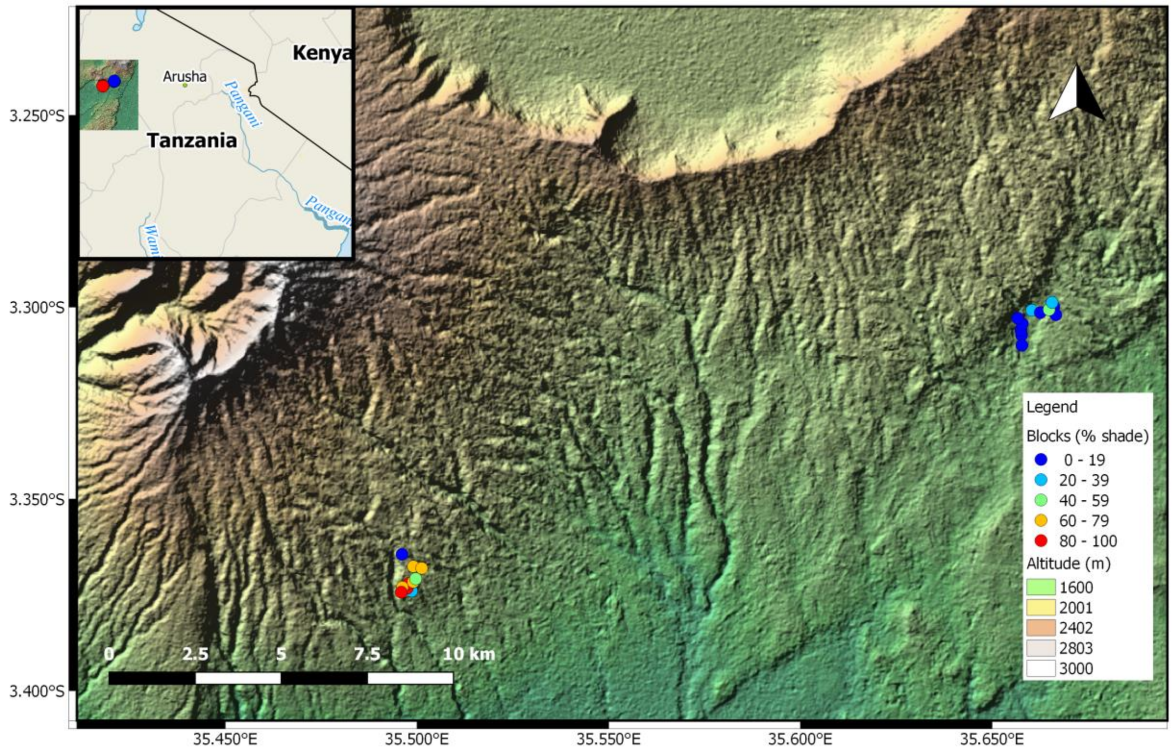

Fig. 4.1. Location of selected blocks of variable percentage shade, associated with altitude.

4.2.2. Microclimatic setup

The microclimatic setup is identical to that described in Chapter 3, but differs in that only 12 iButton Hygrochron (DS1923 Maxim) data loggers were used.

4.2.3. Yield and phenological indices

The quantity of ripe cherry harvested was recorded for each block on a daily basis for the three year period and is represented as yield in $kgha^{-1}$ (Y). Variables include the Julian day (JD, day of year from January 01) at which harvest started (JD_{start}), the Julian day at which the main (greatest) harvest occurred (JD_{main}), the Julian day at which harvest ended (JD_{end}) and total harvest length (JD_{length}). Harvest frequency throughout the entire growing season for each block was recorded and is represented as Y_{freq}. Meteorological variables include (i) mean night-time temperature (T_{night}), (ii) mean daytime temperature (T_{day}), and (iii) mean daily temperature (T_{mean}). Time limits to calculate these means were set at one hour after sunset (19:30h) and one hour after sunrise (07:30h). Mean night-time and daytime temperatures were used as opposed to absolute minimum (T_{min_abs}) and maximum (T_{max_abs}) in order to gain a more accurate representation of temperatures experienced by the plant. Growing degree days (GDD) are typically based on temperature variation from the base temperature of a plant below which there is no growth, which was determined at 10.5°C for *C. arabica* by Pezzopane et al. (2008). GDD were, therefore, calculated from the start of the flowering period to the applicable JD variable, using the following equation:

$$GDD = \sum_{i=1}^{n} = \left(\frac{T_{\max\_abs} + T_{\min\_abs}}{2}\right) - T_b$$

where GDD is the growing degree-days; T_{max_abs} is the maximum daily air temperature (°C); T_{min_abs} is the minimum daily air temperature (°C); T_b is the base temperature (°C) set at 10.5°C (Pezzopane et al., 2008), and n is the number of days elapsed between the start of the crop year/flowering season (01 October) and the JD the fruits were harvested. Unfortunately, flowering dates of each block for each year could not be recorded and thus the start of the crop year/flowering period was set to 01 October. Nevertheless, flowering dates were captured for 70% of total blocks for one year, and of these, 95% of blocks had a main flowering flush on the same day (28 October). Based on physiologically-important limits and previous research outcomes (Craparo et al., 2015; Craparo et al., in review), the mean night time temperature leading up to the different harvest phenophases (T_{night_δ}) was also used in the analysis. Similar to GDD, this variable was calculated by taking the T_{night} from the start of the crop year/flowering period to the applicable JD, using the following equation:

$$T_{night\_\delta} = \frac{\sum_{i=1}^{n} T_{night}}{n}$$

Where T_{night} is the mean night time temperature and n is the number of days elapsed between the start of the flowering season (set as 01 October here) and the applicable JD of harvest, T_{night_δ} represents the applicable variable: T_{night_start}, T_{night_main} and T_{night_end}. Precipitation was calculated as the total daily precipitation accumulated from flowering to the start of harvest (P_{start}) and from flowering to the main (greatest) harvest day (P_{main}). For ease of use, it is assumed that all rainfall would reach the plant and so no losses would occur due to canopy interception or runoff. The quantity of irrigated water supplied was added to precipitation for blocks which received irrigation.

4.2.4. Statistical Analysis

In order to extend the weather dataset, a daily ARIMA (p,d,q) model was built for mean, maximum and minimum temperatures of each block to backcast climate so as to include the entire year of 2013. Pearson's correlation coefficient (r) was used to determine significant relationships between the agrometeorological and phenological variables. All-subsets regression was used as a complementary datamining technique to identify interactions and help select parameters for each model. Relationships which are significant (P-value: <0.05) were then further investigated using linear regression. Diagnostic plots and component residual plots were used to check for model fit and normality of residuals. All statistical analyses were performed using R software version 3.3.0.

4.3. Results

4.3.1. Microclimatic dynamics

Annual T_{mean} ranged from 17.1°C to 19.2°C across all blocks over the entire recording period. At the lower boundary, annual T_{night} of blocks ranged from 14°C to 17.3°C, while annual T_{day} fluctuated from 19.7°C to 24.1°C. As a reference for studies using absolute temperatures, T_{min_abs} ranged from 11°C to 15.6°C and T_{max_abs} from 22.8°C to 31.3°C between blocks. T_{night_start} of the coolest block was 14.3°C, and warmest at 17.8°C. Actual block temperatures for each of these variables are presented in Fig. 4.2. T_{day} and T_{night} are closely associated with other temperature-dependent parameters such as shade and altitude (Table 4.1). Shade cover induces a buffer effect on temperatures, such that a higher percentage of shade results in warmer T_{night} (r=0.50, P=<0.05) and although not statistically significant, a negative correlation to T_{day} (r= -0.32, P=0.06). An increase in altitude results in warmer T_{night} and cooler T_{day}, which may, in part, be explained by the positive correlation between shade and altitude (r=0.50). Blocks at higher altitude have a greater percentage of shade and thus record higher T_{night}. Nevertheless, warmer T_{night} at higher altitude may also be the result of a temperature inversion. P_{start} ranged from 775mm to 1229mm between blocks, whereas P_{main} varied from 778mm to 1229mm. The fact that P_{start} is negatively correlated to T_{night} and positively correlated to T_{day}, and P_{main} is correlated to neither, suggests that these two parameters are not related, most likely due to the additive factor of irrigation.

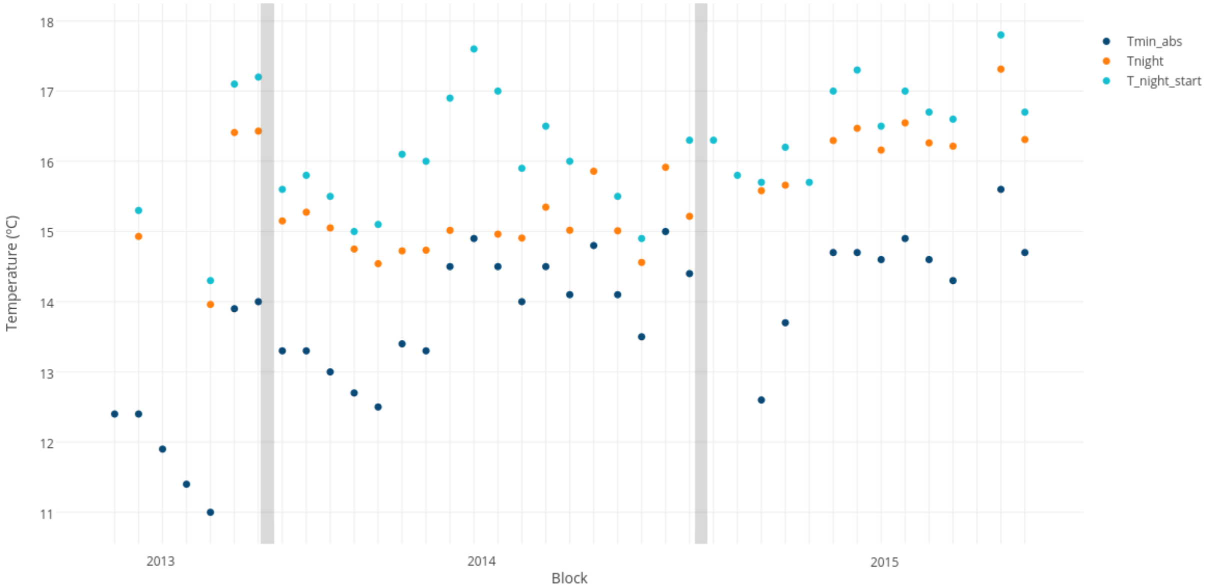

Fig. 4.2. T_{min_abs}, T_{night} and T_{night_start} of each block for the years 2013-2015 (n <=18 blocks)

4.3.2. *JD and GDD trends*

There is an average JD_{start} of 172.6 (SD.: 17.1) across all blocks for the three year period (Fig. 4.3). 2015 had the earliest average harvest start date (167), followed by 2014 (172) and 2013 (183). However, given no significant correlation to JD_{main} and JD_{end}, suggests that an earlier harvest start date does not necessarily imply that other phases occur synchronously. There is also considerable variability between harvest start dates, even those in close proximity with each other. For instance, in 2014 the JD_{start} varies by up to 50 days between two blocks on the same estate. The standard deviation of JD_{main} is double that of JD_{start} at 33.5, and similar to the start of harvest, JD_{end} has a lower standard deviation of 15.9.

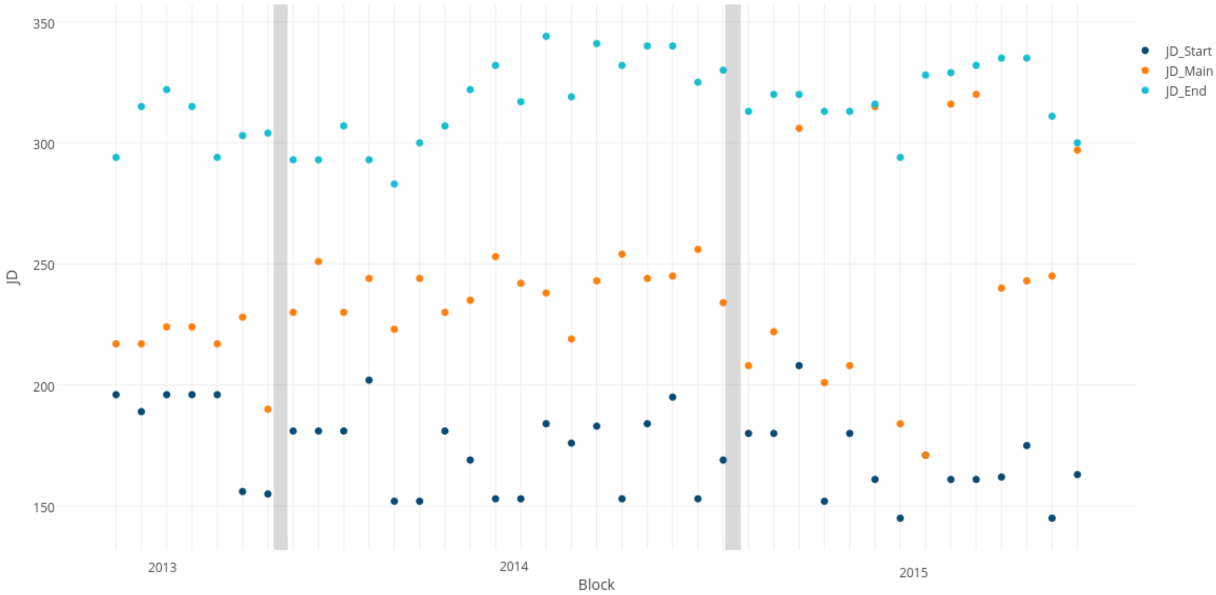

Fig. 4.3. JD of all blocks for the start (JD_{start}), main (JD_{main}) and end of harvest (JD_{end}) for the years 2013-2015 (n <=18 blocks).

4.3.3. *Relationship between meteorological variables and C. arabica phenology*

Of all bioclimatic variables, T_{night_start} has a superseding effect on the timing of harvest onset (Table 1). Higher mean night time temperatures result in an earlier start to harvest (r= -0.76), whereas T_{night_start} of ~14.5°C result in a harvest onset at ~200 Julian days. By contrast, T_{night_start} of ~17.5°C accounts for faster ripening and thus a harvest start at ~150 Julian days, almost two months earlier. The linear regression indicates that an increase of 1ºC in T_{night_start}, results in a harvest start date advance of 15.4 days ($R^{2=}$0.57, P=2.94e-07) (Fig. 4.4). Intrinsically linked to T_{night_start}, T_{night} also has a negative correlation to the start of the harvest season, although the model accounts for less of the variance (R^2=0.35) since it is not specific to that period. Contrary to previous suggestions on drivers of coffee phenology, in our study GDD has no relationship to the start of harvest. Against expectations, P_{start} and P_{main} are both positively correlated to JD_{start}, suggesting a greater accumulation of precipitation results in a later harvest. However, this unlikely association may be disregarded, as Variance Inflation Factors (VIF>2) indicate there is multicollinearity between precipitation variables and JD_{start}. Regression subsets suggest various combinations of regressors with T_{night}, however, interaction terms were omitted since there was a lack of contribution to model variance (R^2).

Table 4.1

Pearson correlation values for meteorological and phenological variables. $T_{night\_}\delta$ represents the different variables (T_{night_start}, T_{night_main}, T_{night_end}) with their associated phenophase (JD_{start}, JD_{main}, JD_{end}).

	GDD	T_{night_δ}	T_{night}	T_{mean}	T_{day}	P_{start}	P_{main}	Altitude	Shade
JD_{start}	-0.03	-0.76***	-0.59***	-0.23	0.13	0.40*	0.38*	-0.40*	-0.35
JD_{main}	-	0.01	0.21	-0.05	-0.13	-0.37*	-0.32*	0.26	0.28
JD_{end}	-	0.27	0.09	-0.50**	-0.06	-0.22	-0.19	0.60***	0.27
Y	-0.07	-0.25	-0.29	-0.25	-0.13	0.26	0.29	-0.24	0.03
Y_{freq}	0.05	0.49*	0.36	0.21	-0.07	0.03	0.51*	-0.31	0.29
JD_{length}	0.14	0.70***	0.52**	-0.18	-0.14	-0.45**	-0.42**	0.72***	0.45**
T_{night}	0.66***	0.84***	1	0.25	-0.09	-0.46**	-0.28	0.45*	0.50**
T_{mean}	-0.02	0.37	0.25	1	0.09	-0.24	-0.24	-0.05	-0.01
T_{day}	0.12	-0.19	-0.09	0.09	1	0.35*	0.30	-0.33*	-0.32
Shade	0.07	0.54***	0.50**	-0.01	-0.32	-0.51***	-0.45**	0.50***	1

* $P < 0.05$ ** $P < 0.01$ ***$P < 10^{-6}$

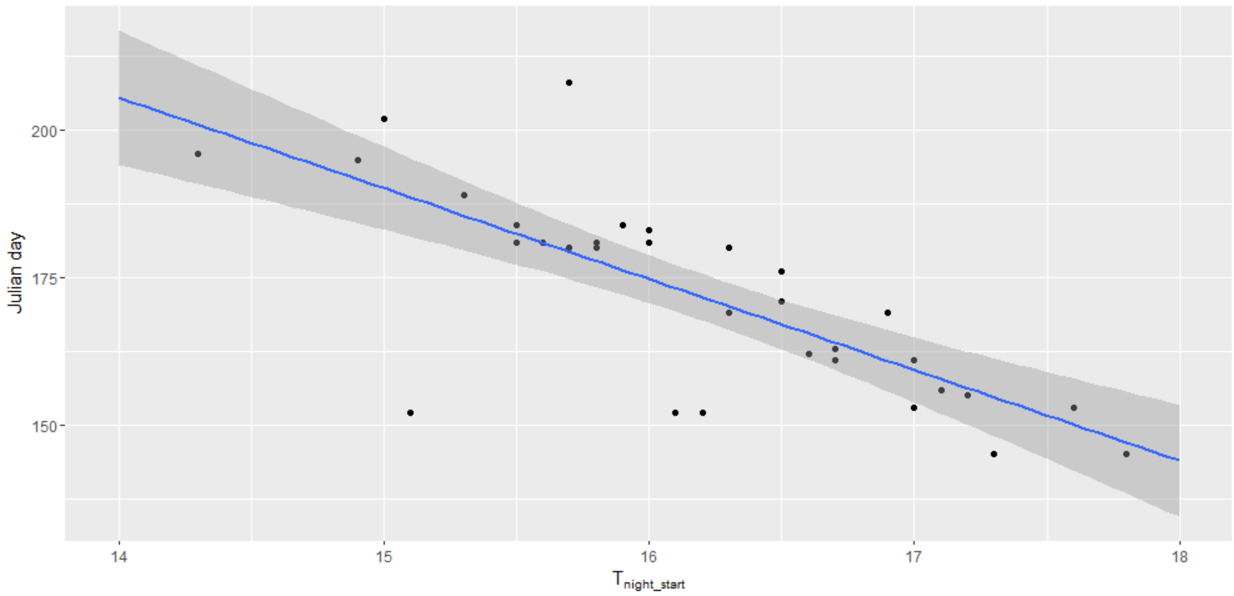

Fig. 4.4. Linear regression of JD_{start} and T_{night_start} with an associated confidence band of 95%.

P_{main} is the only significant parameter related to JD_{main}, with a greater amount of precipitation resulting in an earlier main harvest. Similarly, T_{mean} has a significant negative correlation with JD_{end}. The regression indicates that for every degree Celsius increase in T_{mean}, JD_{end} advances by 17.7 days (R^2=0.25, P=0.002). The positive correlation between T_{min} variables (T_{night} and T_{night_start}) and JD_{length} reinforces that warming night time temperatures cause an advance in ripening and JD_{start}, thereby extending JD_{length}.

In this study, the measurable effect of altitude and shading on plant phenology was limited to the effect these two parameters have on temperature. Therefore, altitude and shading collectively act as a proxy temperature effect on *C. arabica* pheno-phases. The higher percentage of shade at higher altitudes (r=50) raises T_{night}, which in turn results in a negative correlation between JD_{start} and altitude (Table 4.1). This interdependency is further explained by significant correlations between shade, altitude and $JD_{length.}$ Night-time warming result in an advance of JD_{start} which increases JD_{length}. While all temperature variables were negatively correlated to yield, the relationships were not statistically significant. In contrast, increasing T_{night_start} and P_{main} are both statistically significantly associated with a higher frequency of harvest.

4.3.4. *Climate change forecast and influence on C. arabica pheno-phases*

Long-term climate data for the *C. arabica* growing region of N-Tanzania demonstrate a significant increasing temperature trend since 1960 (Craparo et al., 2015). T_{min_abs} are increasing most rapidly at 0.31°C/decade (P = 8.547e-12), while those for T_{max_abs} are increasing at 0.24°C/decade (P = 1.177e-06) (Craparo et al., 2015). Should temperatures continue to rise as they have during the past five decades, then T_{min_abs} in the Ngorongoro region is expected to have increased by 1ºC by the year 2050, using a base temperature in 2010 (Fig. 4.5. MAPE = 1.4). This is in accordance with the GCM forecasts and IPCC projections for the region, associated with a 2.8°C rise by 2100 (Meinshausen et al., 2011). Therefore, based on the T_{night_start} and JD_{start} regression, increased warming would mean a harvest start ~15 days earlier in 2050.

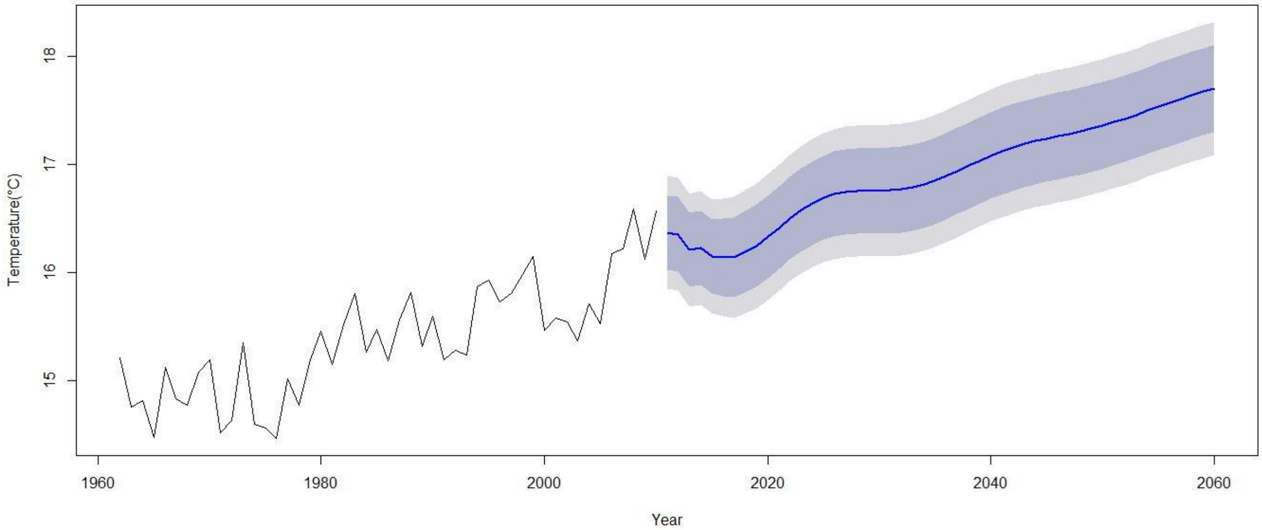

Fig. 4.5. ARIMA (5,1,2) model with forecasted T_{min_abs} for the period 1962–2060, with confidence vs. prediction intervals (after Craparo et al., 2015).

4.4. Discussion

4.4.1. C. arabica phenology and microclimate

These data demonstrate how increasing night time temperatures affect the timing of harvest onset dates. Recently, Jung et al. (2016) demonstrated how warming temperatures (specifically night time temperatures) have a superseding effect on budburst and flowering in plants. The authors found that phytochromes in plants change states at night, becoming thermoreceptors. In their active state, phytochrome molecules bind themselves to DNA to restrict plant growth. If a plant is suddenly subjected to shade, phytochromes are quickly inactivated, enabling it to grow faster to find sunlight again. However, the reverse is true at night. Instead of rapid deactivation, molecules progressively change from their active to inactive state, at a directly proportional rate to temperature. Thus, cooler night temperatures result in a slower transition, with consequent prolonged growth (Jung et al., 2016). Further, supra-optimal temperatures may cause an increase in photosystems and thylakoid electron transport (a key process of photosynthesis) of *C. arabica*, even up to temperatures of 37/30ºC (day/night respectively) (Rodrigues et al., 2016). As a consequence of excessive warming, vegetative growth and reproductive activity is accelerated (Damatta and Ramalho, 2006). Depending on when flowering commenced, an earlier JD_{start} could result in a reduction of the berry filling and ripening phase. A shorter ripening phase has been linked to reduced bean density and sensory quality of the beverage (Da Silva et al., 2005; Vaast et al., 2006; Joët et al. 2010). Several factors have been proposed to initiate inflorescence, however, most agree that flower induction is related to temperature changes (day / night) and potentially a synergistic effect with water deficit (Ramirez et al., 2010). Although flowering data were not captured, one year of data indicate that 95% of recorded blocks had a main flowering on the same day; therefore, this advance in JD_{start} is likely to shorten the ripening phase.

The timing of the major harvest event (JD_{main}) does not seem to be influenced by any meteorological parameters other than increasing precipitation, resulting in an earlier JD_{main}. Increasing precipitation during the ripening phase is also positively linked to Y_{freq}. This is in accordance with research on the flowering period, which illustrates how the occurrence of sporadic and low-intensity rains, 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). Increasing T_{night_start} also result in an increase in harvest frequency, necessitating the need for more labor, which would undoubtedly increase costs to the farmer. Evidently, the length of harvest is heavily dependent on temperatures and related proxy variables (shade and altitude), and the effect these have on JD_{start} and JD_{end}. The apparent negative correlation between P_{start}, P_{main} and JD_{length} may not necessarily be a true effect, but rather collinearity, since neither of the precipitation variables determine when JD_{start} or JD_{end} occur.

It should be emphasized that T_{night} are the mean night time temperatures, not the absolute minimum temperatures. As indicated above, there is an ~2°C difference between T_{min_abs} and T_{night}. Given that temperatures in these blocks remain below the T_{night} inflection point (17°C), this may explain the lack of correlation between temperature variables and yields, since previous studies demonstrate how increasing temperatures result in a decline in environmental suitability and yields (Bunn et al., 2015; Craparo et al., 2015). Furthermore, these data are representative of commercial coffee estates with good agricultural technology and access to inputs, therefore limiting factors to bean development from increasing T_{night} may be compensated for with irrigation, fertilizers and other inputs (Craparo et al., in review). Given that temperatures have only started increasing rapidly since 1970 (IPCC, 2007; Williams and Funk, 2011) and only recently approached the upper limit suitable for cultivation, this may explain why no observed trend of advancing JD with respect to harvest onset has been recorded in previous years.

4.4.2. *Implications for C. arabica phenology and adaptation strategies under a future climate warming scenario*

Mean T_{min_abs} have increased by 0.31°C/decade (P = 8.547e-12) since 1960 (Craparo et al., 2015). Forecasts from this ARIMA model indicate that T_{min_abs} will breach another 1ºC increase by the year 2050 (Craparo et al., 2015). Based on the robust relationship between T_{night_start} and JD_{start}, this would mean that the respective harvest start dates of each coffee growing region would occur ~15 days earlier. With detrimental effects to plant physiology already observed from increasing temperatures (e.g. Davis et al., 2012; Bunn et al., 2014, 2015; Craparo et al., 2015), this shift in phenological timing may have further negative implications for *C. arabica* production. Large-scale climatic forces such as the Indian Ocean Sea Surface Temperatures (SSTs) and El Niño-Southern Oscillation (ENSO) are primarily responsible for changes in temperature and precipitation in Tanzania (Pepin et al., 2010; Williams and Funk, 2011). Temperature changes are expected to occur concomitantly with changes in precipitation (Hartmann et al, 2013), and thus the observed advancing harvest dates should occur in parallel with advancing rainfall. If, however, these two meteorological variables do not change equally, increasing T_{night} would significantly advance JD_{start}, but the supporting precipitation required for correct physiological development may not deliver.

Regardless of the synchrony in change between temperatures and rainfall under an expected future warming scenario, adaptation mechanisms for *C. arabica* are imperative. Advances in harvest dates may result in reduced bean quality (Da Silva et al., 2005; Vaast et al., 2006; Joët et al. 2010), unsynchronized fruit ripening (DaMatta et al., 2008), and likely reduced yields (Peters and Carroll, 2012). These factors in turn would result in considerable increases in production costs and financial losses to the farmer. In particular, it is urged that adaptation strategies should focus on reducing the warming trend of night time temperatures. T_{min_abs} have increased at almost double the rate of T_{max_abs} since 1960 and are thus largely responsible for the increasing T_{mean} (Craparo et al., 2015). Despite the accepted optimal temperature range of

18-21ºC for *C. arabica* (Alègre, 1959), these results support other findings which advocate a preference for lower temperatures (Gay et al., 2006; Craparo et al., 2015; Bunn et al., 2015).

The typical relationship between temperature and altitude suggests that higher areas would be more appropriate for cultivation; this is, however, complicated by the agroecological system influencing micro-climates. As illustrated, shade increases T_{min} but does not reduce T_{max}. However, shade cover is an intrinsic part of many smallholder production systems with numerous benefits such as the recycling of nutrients and soil organic matter sustenance, enhanced coffee quality, increased biodiversity, and improved livelihood security (e.g. cash crops from fruits or timber) (Vaast et al., 2006; Lin, 2010; Jha and Dick, 2010). Therefore, factors other than coffee production would need to be accounted for when selecting adaptation mechanisms or climate smart agroforestry systems.

4.5. Conclusion

Using high resolution microclimatic data from Tanzania, this study shows how warming night time temperatures have a superseding effect on the timing of coffee harvest. In particular, T_{night_start} enables the accurate prediction of the beginning of harvest season. Rainfall and irrigation have little impact on the timing of harvest, although increased P_{main} may cause an earlier onset of the main harvest. Data indicate a strong relationship between T_{night_start} and JD_{start}, whereby a T_{night_start} of ~14°C results in harvest beginning on a Julian day of ~200. In contrast, a T_{night_start} of ~18°C would result in a Julian harvest start day of ~145 (i.e. almost two months earlier). Based on model forecasts, Tanzania will experience a further increase of 1ºC in T_{min_abs} by 2050. A progressively advancing harvest date could have negative implications for the coffee industry by reducing bean quality, causing unsynchronized fruit ripening, substantially reducing yields, and prolonging the harvest period with associated increasing labour costs. This is predominantly owing to a reduced berry filling period and potential loss of synchrony between the berry filling and rainfall periods. Suggested adaptation strategies should place emphasis on reducing the rate of T_{night} increases. However, given the complex nature of the smallholder coffee system which still supplies the bulk of coffee production, these measures cannot be implemented without appropriate local stakeholder involvement and buy-in.

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CHAPTER 5

Application of thermography for monitoring stomatal conductance of *Coffea arabica* under different shading systems

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Abstract

Stomatal regulation is a key process in the physiology of *Coffea arabica* (*C. arabica*). Intrinsically linked to photosynthesis and water relations, it provides insights into the plant's adaptive capacity, survival and growth. The ability to rapidly quantify this parameter for *C. arabica* under different agroecological systems would be an indispensable tool. Thus, for the first time, this study demonstrates the use of thermography on *C. arabica* as a complimentary or alternative technique to traditional methods such as porometry. Using a Flir E6 MIR Camera, an index that is equivalent to stomatal conductance (I_g) was compared with stomatal conductance measurements (g_s) in a mature coffee plantation. In order to account for varying meteorological conditions between days, the methods were also compared under stable meteorological conditions in a laboratory and I_g was also converted to absolute stomatal conductance values (g_1). In both the plantation and the laboratory, two plots representing full sun and full shade cover were considered. In contrast to typical plant-thermography methods which measure indices once per day over an extended time period, high resolution hourly measurements were taken over daily time series with 9 sun and 9 shade replicates. The results reveal a fair correlation between I_g and g_s and demonstrate the success of using thermography to reflect variation in stomatal conductance of coffee canopies *in situ*. Including several other meteorological parameters in the calculation of g_1 did not contribute to any stronger correlation between methods. The method is particularly useful for situations where absolute values of stomatal conductance are not required, such as for comparative purposes, screening or trend analysis. The findings are used to advance the protocol for a more accurate methodology which may assist in quantifying advantageous microenvironment designs for coffee, considering the current and future climates of coffee growing regions.

Keywords: Agroforestry, climate change, climate smart agriculture, infrared thermography, shade, stomatal conductance

5.1. Introduction

The coffee industry supports an estimated 125 million people worldwide, with the vast majority of farmers located in Africa (Pendergrast, 2010; ICO, 2015). However, several areas are approaching, or have surpassed the suitable environmental growing limits of *C. arabica*, thus compromising yield quantity (Craparo et al., 2015), with modelling projections depicting further losses (Bunn et al., 2014, 2015). High spatio-temporal resolution climate data from Ngorongoro, Tanzania, indicate how the immediate environment and microclimate influence coffee yields and harvest phenology (Craparo et al., (a) unpublished; Craparo et al., (b) unpublished). Furthermore, depending on the cropping system, certain variables (shade, sunlight, altitude) may either ameliorate or exacerbate the effects of climate change on the crop (Bertrand et al., 2016). The design structure of the microenvironment is therefore fundamental for climate change adaptation. These decisions will also have other important consequences for aspects such as climate change mitigation, ecosystem services and livelihood security (Vaast et al., 2006; Lin, 2010; Jha and Dick, 2010). Gaining rapid insights into the status of the plant's condition in different environments is thus a crucial tool, especially in light of future climate projections and the need for effective site-specific adaptation strategies (Bunn et al., 2014: 2015; Craparo et al., 2015; Läderach et al., 2016).

Leaf stomata allow the plant to rapidly adapt to changing biotic and abiotic stimuli (Chaves et al., 2003). By regulating leaf gas exchange fluxes (CO_2 and H_2O), stomata are responsible for maintaining equilibrium in the plant. There is a constant compromise between maximizing photosynthetic gains, while minimizing water loss (Jones, 2014). A byproduct of these fluxes is the regulation of canopy temperature (T_{canopy}). As stomata open, water loss occurs through leaf transpiration which consequently cools the plant. However, under sub-optimal conditions such as soil water deficit, high vapour pressure deficit (VPD) or high irradiance, transpiration may cease, thereby resulting in an increase in leaf temperature (T_{leaf}) (Hetherington and Woodward, 2003). Stomatal conductance of *C. arabica* is generally high in the morning and decreases throughout the day as irradiance and VPD rise. This relationship is best described by a curvilinear decay function (DaMatta and Ramalho, 2006). Monitoring stomatal conductance to water vapor (g_s) and/or transpiration, provides insights into the plants' interaction with the immediate microenvironment. However, typical methods such as leaf gas exchange measurements or porometry are not without limitations. These methods require contact with the leaf, which often interferes with leaf functioning, and are also limited in their ability to capture spatial and temporal variability at the plant canopy level (Costa et al., 2013). Individual leaf measurements are also time consuming depending on sample size (Struthers et al., 2015).

Thermal imaging (thermography) is a rapid and effective technique used to remotely measure stomatal parameters (Jones et al., 2009). Using the variability in T_{canopy}, thermography makes it possible to estimate g_s and transpiration. With recent advances in sensor affordability and improved methodology, the technique has been successfully applied on a variety of annual and perennial plant species across diverse environments (e.g. Jones et al., 2009; Durigon and de Jong van Lier, 2013; Ballester et al., 2014; Struthers et al., 2015; Maes et al., 2016). The inherent nature of thermography means it can be applied to almost any spatial and temporal scale, from seedlings in laboratories to individual leaves, plant canopies and entire field crops (Jones et al., 2009). The technique has therefore been successfully used to investigate several phenomena such as abnormal stomatal closure, genetic variation in stress tolerance and the influence of different management techniques on plant water status and phenotyping (Costa et al., 2013).

As leaf temperature is influenced by environmental conditions such as air temperature, wind speed, humidity and incident radiation, a number of attempts have been made to normalize the data to account for varying environmental conditions (Jones et al., 2009). For instance, Jackson *et al.* (1977) used differences between air temperature (T_a) and T_{leaf} as a measure of plant stress. Further to this, Idso et al. (1981) developed the 'Crop Water Stress Index' (CWSI) which relates the observed temperature to the minimum (non-stressed) and maximum (non-transpiring) temperatures of a reference crop under similar environmental conditions. However, a limitation when using this index is that it requires the user to determine temperature baselines for the specific well-watered crop and VPD at each measurement (Costa et al., 2013). In addition, this index does not factor in changes in T_{canopy} due to irradiance and wind speed, and the baselines may change with different radiation conditions (Costa et al., 2013).

Building upon this index, Jones (1999) developed an alternative approach which uses physical wet and dry reference surfaces, mitigating the downfalls of the original CWSI. More specifically, as the references are within the same environment as the crop in question, there is no need for the theoretical estimation of baselines as they will be exposed to the same conditions (VPD, wind speed, radiation) as the canopy of interest at the time of measurement (Costa et al., 2013). Temperatures for the baselines are easily obtained in each image, either by using artificial reference surfaces (Grant et al., 2016; Maes et al., 2016), or by spraying leaves with water to replicate a fully transpiring leaf (T_{wet}) and covering with petroleum jelly to artificially close stomata (T_{dry}). Another useful index which can be calculated from these parameters is the thermal index of relative stomatal conductance (I_g) (Jones, 1999). Unlike the CWSI, I_g is linearly proportional to g_s, but only for a constant boundary layer conductance (Jones et al., 2009). In order to derive absolute values of stomatal conductance from I_g, it is necessary to account for variability in wind speed (u) and T_a.

Considering the potential benefits of thermography in current coffee agroecological research, the objective of this study is to investigate the applicability of this method as an alternative or complementary technique to quantify stomatal conductance of *C. arabica*. Accordingly, the aim is to outline successful methods for determining I_g of coffee in the field, under two shading systems. In order to gain the most accurate understanding of the relationship between I_g and g_s, the focus of this study is the association at the leaf level over highly variable (daily) time series. Due to fluctuating meteorological conditions in the field, the same methodology was repeated in the laboratory under stable meteorological conditions. Furthermore, I_g was also converted to absolute stomatal conductance g_1, using a scaling factor which accounts for the variability in boundary layer conductance (G) and temperature. The study elaborates on important findings which may assist in advancing the protocol for canopy and plantation level analysis on coffee. Finally, the novelty of this method for determining the influence of different agroecological systems on coffee and under future climate scenarios is presented.

5.2. Materials and Methods

5.2.1. Study region and experimental design

In order to achieve the best possible representation of coffee growing systems, this study was conducted on a plant in full sun and full shade in a commercial coffee estate in South Africa. In order to gain a degree of meteorological control, the experiments were also performed on a plant in full sun and full shade in a laboratory. The rationale for the laboratory experiment was not to understand whether this method may be suitable for this environment, but rather to determine if the highly fluctuating meteorological conditions during the field study did in fact distort measurements extensively. The experiments were performed over three separate periods during 2015 and 2016. Hourly measurements starting from 06:00 and ending at 16:00 were undertaken on a plant in full sun and full shade with 9 daily replicates, providing 18 series in total. Days 1-5 correspond to the coffee estate and 6-7 to the laboratory setting. One sun and one shade plant were measured on each of the days 1, 2 and 3, while two sun and two shade plants were measured on days 4 and 5. The commercial coffee estate is one of the most southerly located coffee plantations in the world at 31º02'S and 30º10'E, at an altitude of 220 m.a.s.l. The estate has no irrigation and cultivars SL28 and F6 are currently farmed. Measurements took place on the SL28 cultivars during the peak rain season toward the end of flowering in November 2015 (days 1-3) and November 2016 (days 4 and 5). The laboratory environment was selected to minimize influence from meteorological parameters such as wind and precipitation, while allowing control over the amount of light delivered. Temperature, humidity and air circulation were not manipulated and followed typical, though muted, daily fluctuations from two open windows in the laboratory. Two 4-years-old potted coffee plants (SL28 cv.) were used. One plant received ambient light through a window, representing a shaded system with a maximum PAR (photosynthetically active radiation) of 90 µmol m^{-2} s^{-1}. The second plant was grown under a grow light (Cree CXB3590, Cree Inc.) customized for the typical PAR range (400 to 700 nm) which represented a full sun system. The light delivered a low output of 350 µmol m^{-2} s^{-1}.

5.2.2. Meteorological measurements

A TinyTag Plus 2 (Gemini TGP-4020, West Sussex, UK) and an iButton Hygrochron (DS1923 Maxim, San Jose, U.S.) were used in both the field and laboratory to record temperature and humidity respectively throughout the experimental period. The TinyTag loggers have an external thermistor probe and measured temperature (T_a) at 30 minute intervals with a resolution of ±0.02°C. iButtons recorded temperature and humidity at 30 minute intervals, with a resolution of ±0.5°C and ±0.6%. Loggers were suspended in a Stevenson-type screen which consisted of a 200 mm long x 100 mm wide white PVC tube covered in aluminium foil and were installed inside the coffee plant canopy at 1 m above ground in both the plantation and laboratory. Wind data were obtained from the Port Shepstone weather station (~40 km away).

5.2.3. Thermal imaging

Thermal images were obtained with a Flir E6 mid-wave infrared camera producing images of 160 x 120 resolution with an accuracy of ±0.06°C. Three leaves (two representing reference surfaces and one representing T_{canopy}) were randomly chosen in the upper one-third of the canopy and the adjacent stem was marked to ensure the exact same leaves were used for each measurement period (Fig. 5.1). The youngest fully expanded leaves, corresponding to the second pair from the apex of the plagiotropic branches, were chosen. For each image, the background temperature required for calculation of object temperature was obtained by reading the radiative temperature of a crumpled sheet of aluminum foil (near black body). The foil was placed at the same location of the selected leaves, with camera emissivity set to 1.0. Images were taken on the upper (adaxial) side of the leaf at a lateral position to the canopy. In order to obtain the most accurate radiative temperature for each desired reading, a minimum of two photos were taken. The average temperature of each individual leaf was calculated on each image and then the mean temperature of the two recordings calculated per leaf. All image processing and analysis was undertaken in Flir Tools software version 5.2.15161.

5.2.4. Stress indices and reference surfaces

Following on from the work by Jones (1999, 2014), reference surfaces were used in order to mitigate the need for detailed environmental information. Actual leaves were used as reference surfaces for each recording. The leaves were either sprayed with water on one side of the leaf (adaxial) ~1 minute before imaging (=T_{wet}), or covered with petroleum jelly on both sides ~5 minutes before imaging (=T_{dry}) (Fig. 5.1) (Guilioni et al., 2008). The reference leaves, as well as untreated leaves (=T_{canopy}), were of similar characteristics and selected beside one another in order to homogenize identical weather conditions between the three leaves. Careful image analysis was subsequently conducted to prevent the inclusion of non-leaf material (twigs, branches, soil). I_g of hypostomatous leaves takes the form (Guilioni et al., 2008):

$$I_g = \frac{(T_{dry-}\, T_{canopy})}{(T_{canopy-Twet})} = \frac{\gamma\, r_{aV+}\;\; s\, rHR}{\gamma\, r_s} \qquad \text{(Equation 1)}$$

Where γ is the psychrometric constant (kPa K^{-1}), r_{aV} is the resistance to vapour transport in the boundary layer (s m^{-1}), s is the slope of the curve relating T_a with saturated vapour pressure (Pa K^{-1}), r_{HR} is the leaf resistance to sensible heat transport and radiative heat loss (sm^{-1}) and r_s is the leaf stomatal resistance (s m^{-1}). I_g is linearly proportional to g_s as long as the boundary layer conductance (G) remains constant. As demonstrated by Maes and Steppe (2012), G seldom changes with g_s, incoming solar radiation (K_{in}) and VPD, but is strongly influenced by *u* and

T_a. Since these experiments took place over variable meteorological conditions, I_g was converted to stomatal conductance values (g_1) using the equation:

$$g_1 = I_g \frac{\gamma}{\gamma\, r_{aV} + s\, rHR} = I_g\, G \qquad \text{(Equation 2)}$$

Whereby, $G = \frac{\gamma}{\gamma\, r_{aV} + s\, rHR}$

n this equation, G represents a scaling factor that depends on the magnitude of the boundary layer resistance and temperature. The derivation of r_{aV} (after Jones, 2014) follows:

$$\mathrm{raV} = 0.92 \times \mathrm{rHR} \qquad \text{(Equation 3)}$$

with rHR (after Maes and Steppe, 2012):

$$\mathrm{rHR} = \frac{r_{aH} \times r_R}{r_{aH} + r_R} \qquad \text{(Equation 4)}$$

Leaf resistance to sensible heat transfer (r_{aH}) can be estimated with the equation (Guilioni et al., 2008):

$$r_{aH} = \alpha \left(\frac{d}{u}\right)^{0.5} \qquad \text{(Equation 5)}$$

Where, d is the characteristic leaf dimension (m), u is wind speed (ms^{-1}) and the coefficient α is approximately equal to 200. The virtual leaf resistance to radiative transfer (r_R) ($s\ m^{-1}$) is calculated as (Jones, 2014):

$$r_R = \left(\frac{\rho_a\, C_\rho}{4\varepsilon\sigma T_a^3}\right) \qquad \text{(Equation 6)}$$

Where, ρ_a is the air density ($kg\ m^{-3}$), C_P is the heat or thermal capacity of the air ($J\ kg^{-1}\ K^{-1}$), ε is the overall emissivity, σ is the Stefan-Boltzmann constant ($5.675\ 10^{-8}\ W\ m^{-2}\ K^{-4}$) and T_a is the air temperature (K or °C).

5.2.5. Stomatal conductance

Stomatal conductance (g_s) was measured using a leaf porometer (model SC-1, Decagon Devices, Inc., Pullman, WA, USA) with an accuracy of ±10%. The instrument was calibrated prior to each set of measurements, following the manufacturer's guidelines. The same leaf selected for T_{canopy} was used for stomatal conductance measurements. Recording took place immediately after thermal images were taken, so that the porometer did not distort leaf temperature or functioning. Three measurements per leaf were taken on the abaxial side and averaged to represent the g_s of that leaf. The time taken to measure each leaf was ~5 min per canopy. Limiting the number of leaves on which to measure stomatal conductance permits the thermal readings to be completed within 5 minutes of stomatal conductance measurements, thereby minimizing the variability in conductance due to meteorological factors.

5.2.6. Statistical analyses

Pearson's correlation coefficient (r) was used to determine significant relationships between thermal indices and stomatal conductance measurements. Granger causality tests were used to identify any lagged relationships between thermal indices and stomatal conductance. All statistical analyses were performed using R software version 3.3.0.

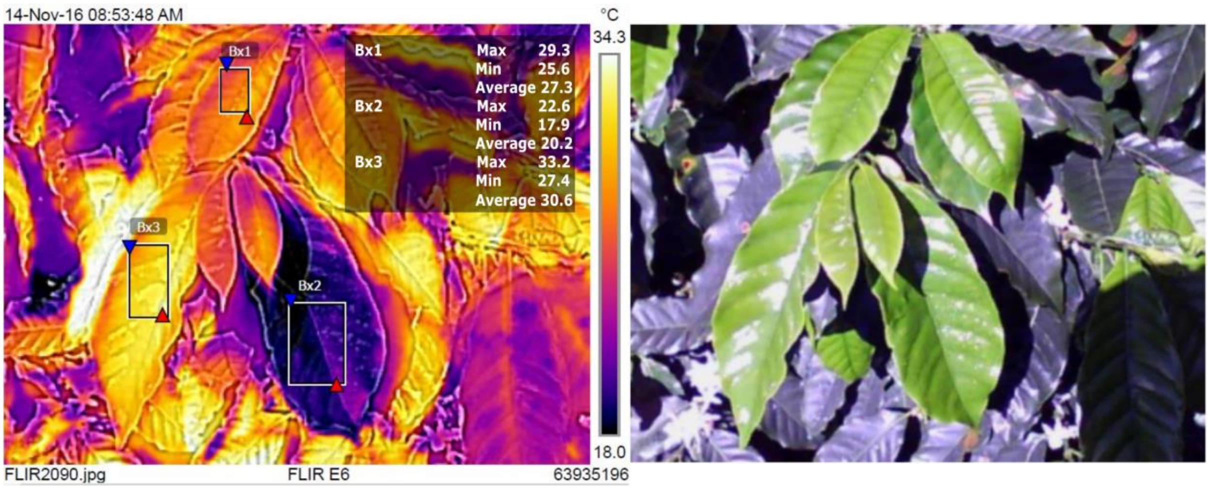


Fig. 5.1. Thermal (left) and corresponding RGB image (right) of the reference surfaces. Bx1, Bx2 and Bx3 represent T_{canopy}, T_{wet} and T_{dry}, respectively. The minimum, maximum and mean value for each reference surface is illustrated.

5.3. Results

5.3.1. *Microclimatic dynamics*

The estate had a T_{mean} of 20.3°C, mean T_{min} of 16.4°C and mean T_{max} of 30.7°C over the experimental period for days 1 to 5 (Fig. 5.2a). VPD values are not included for the first three days owing to a malfunctioning hygrometer, but ranged from 0.05 kPa to 0.97 kPa for the remainder of the experimental period (Fig. 5.2b). Given close proximity of the Indian Ocean, there were several days with substantial wind, with either the dominant NE, or SW blowing each day (Fig. 5.2c). Wind speed generally peaked at midday, with gusts reaching a maximum of 15.1 m s^{-1}. In contrast, temperatures in the laboratory remained at a stable T_{mean} of 23.3°C, mean T_{min} of 22.6°C and mean T_{max} of 24.0°C. VPD ranged from 0.38 kPa to 0.98 kPa during the experimental period and no wind was recorded in the laboratory during days 6 and 7, and thus ignored.

5.3.2. *Stomatal conductance and thermal indices*

Despite high diurnal variability, I_g and g_s approximated each other throughout the day in each setting, with a correlation for all pooled data points of r=0.58 (P= 1.77e-14) (Fig. 5.3). Individual daily correlations of I_g and g_s ranged from 0.35 to 0.90, with each time series displayed in Fig. 5.4. Correlation values for each daily series are outlined in Table 5.1. Granger causality tests indicate there was no lagged relationship between I_g and g_s. When incorporating variability in boundary layer conductance, the daily time series relationship between g_s and g_1 was exceptionally similar to g_s and I_g, with only one instance (series 6) providing a better correlation. Stomatal conductance typically peaked in the morning and late afternoon, however, the trend varied for each system and between each day. It should be noted that these trends do not represent whole canopy conductance, but rather a single leaf, which was selected primarily to ascertain synchrony between sensing methods.

Contrary to expectations, the greater uniformity of meteorological variables (wind speed, temperature and humidity) in the laboratory (series 8 and 9) did not result in stronger correlations between the two methods when compared with those in the field (Table 5.1). There was no overall correlation between VPD and I_g, and VPD and g_s, for all data points (r=0.15 and 0.18, respectively). However, when each individual daily time series was considered, the correlations between stomatal conductance measurements and VPD ranged from -0.70 to 0.67 (Table 5.2). Increasing *u* had no correlation to I_g and g_s for all data points (r=0.03 and 0.23, respectively). However, there was only one series with a statistically significant negative correlation to g_s (Table 5.2), and accordingly, no association between u and the strength of correlation between I_g and g_s.

The correlation between I_g and g_s for all data in the full sun setting (all pooled full sun time series) was 0.58, while that for the full shade series was slightly higher at 0.65. While there is no clear distinction whether measurements taken in the sun or in the shade were more representative of stomatal change, there were a greater number of significant correlations for shade-based measurements (Table 5.1). Sun-exposed leaves had a greater variability in leaf temperature (T_{leaf}) across the leaf surface than those in shade, with a standard deviation of 3.5°C and 1.3°C, respectively. The standard deviation was calculated over the full diurnal time series. Similarly, g_s of leaves in the sun had an average standard deviation of 34.3 mmol m^{-2} s^{-1} for a leaf, compared to 22.5 mmol m^{-2} s^{-1} for a leaf in shade.

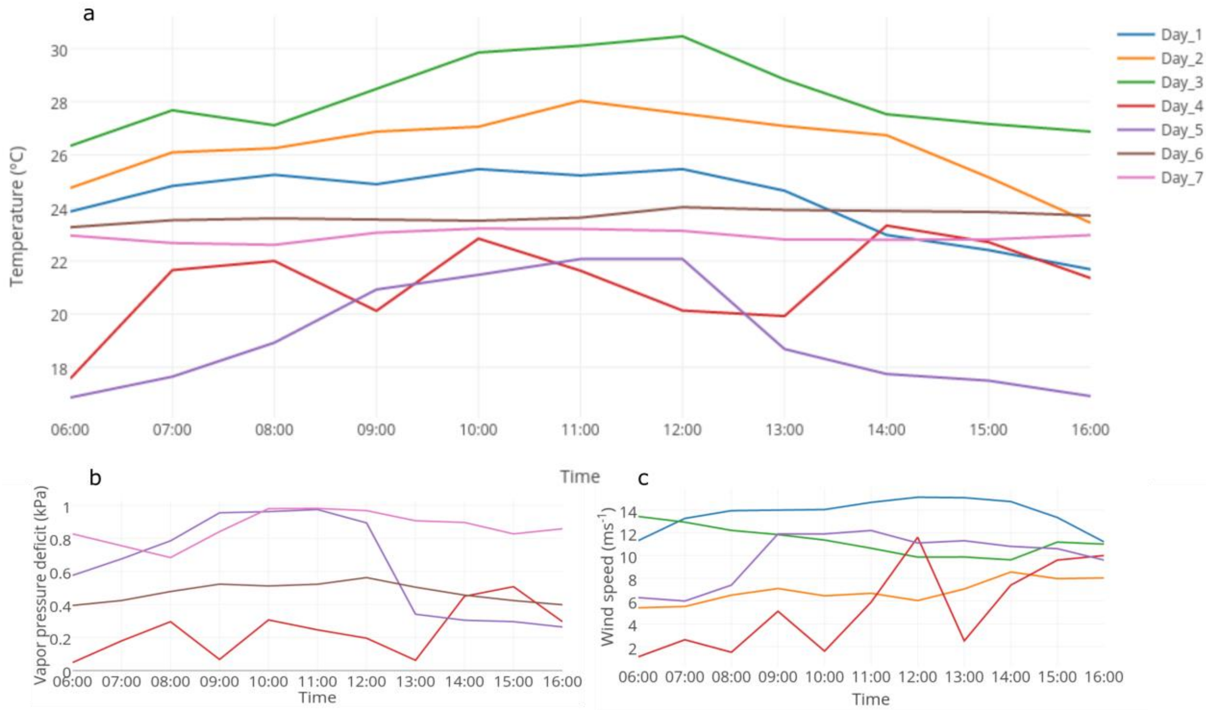


Fig. 5.2. a) Air temperature (T_a), b) vapour pressure deficit (VPD) and c) wind speed (u) measured at the coffee estate (days 1 to 5) and in the laboratory (days 6 and 7). VPD for days 1, 2 and 3 is not included owing to a malfunctioning hygrometer; and u in the laboratory (days 6 and 7) was negligible.

Table 5.1

Pearson correlation values between I_g, g_s and g_1 for each series. Series 1 to 7 are from the coffee estate, while 8 and 9 are from the laboratory.

	Day_1	**Day_2**	**Day_3**	**Day_4**		**Day_5**		**Day_6**	**Day_7**
	Series_1	**Series_2**	**Series_3**	**Series_4**	**Series_5**	**Series_6**	**Series_7**	**Series_8**	**Series_9**
Sun	g_s	g_s	g_s	g_s	g_s	g_s	g_s	g_s	g_s
I_g	0.83**	0.35	0.49	0.78**	0.53	0.44	0.68*	0.43	0.72*
g_1	0.87***	0.49	0.34	0.62*	0.53	0.70*	0.74**		
Shade	g_s	g_s	g_s	g_s	g_s	g_s	g_s	g_s	g_s
I_g	0.49	0.63*	0.36	0.90**	0.70*	0.66*	0.65*	0.80**	0.49*
g_1	0.51	0.53	0.37	0.97***	0.47	0.65*	0.62*		

* $P < 0.05$ ** $P < 0.01$ *** $P < 10^{-6}$

Table 5.2

Pearson correlation values between stomatal measurements (I_g, g_s), wind speed (u) and vapour pressure deficit (VPD) at the coffee estate (days 1 to 5) and in the laboratory (days 6 and 7). VPD for days 1, 2, 3 is not included owing to a malfunctioning hygrometer; and u in the laboratory (days 6 and 7) was negligible.

	Day_1		**Day_2**		**Day_3**		**Day_4**				**Day_5**				**Day_6**		**Day_7**	
	Series_1		**Series_2**		**Series_3**		**Series_4**		**Series_5**		**Series_6**		**Series_7**		**Series_8**		**Series_9**	
SUN	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s
u	0.16	0.47	-0.39	0.40	-0.53	-0.27	-0.17	-0.21	-0.35	-0.62	-0.35	0.58	-0.44	-0.20				
VPD							-0.31	-0.21	0.14	-0.18	0.37	0.67*	-0.12	-0.31	0.30	0.43	0.36	0.17
SHADE	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s	I_g	g_s
u	0.33	0.25	-0.39	-0.49	-0.03	0.31	-0.62	-0.52	-0.49	-0.73*	0.46	0.33	0.44	0.23				
VPD							-0.22	-0.42	-0.42	-0.21	0.10	0.57	-0.34	-0.11	-0.12	0.09	-0.24	-0.71*

* $P < 0.05$ ** $P < 0.01$ *** $P < 10^{-6}$

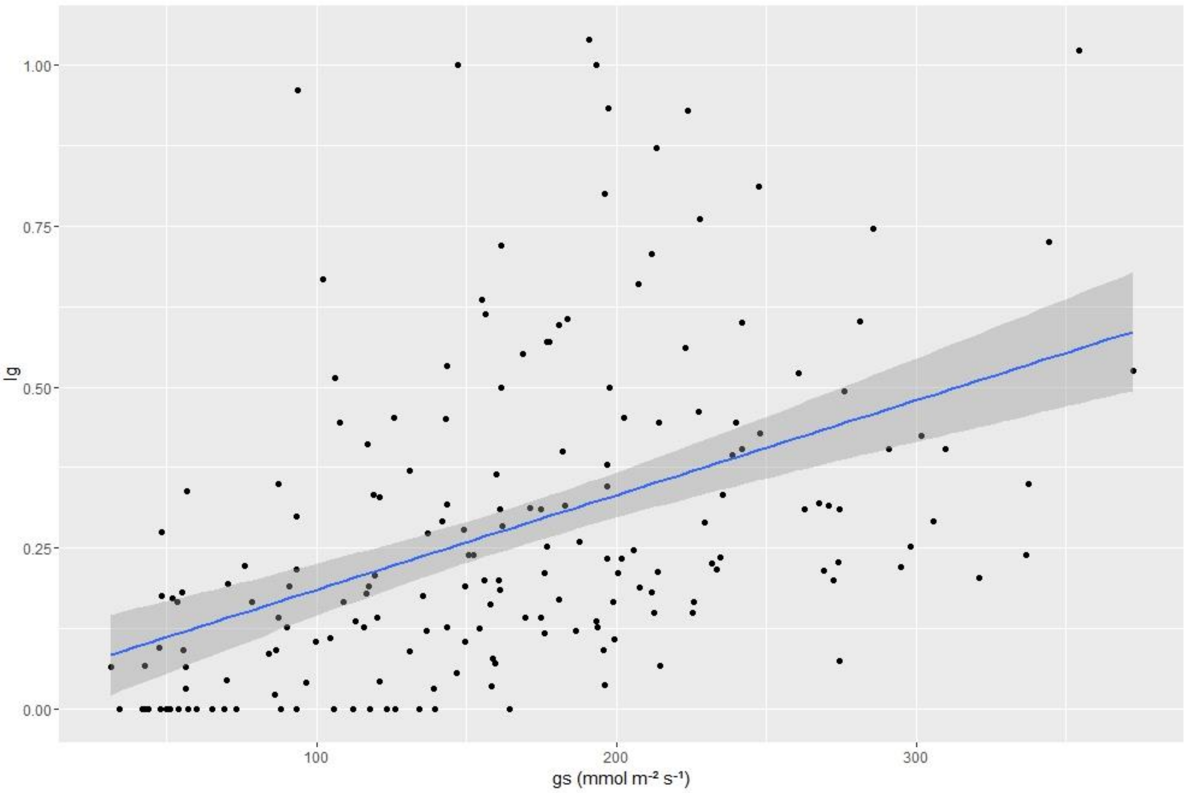
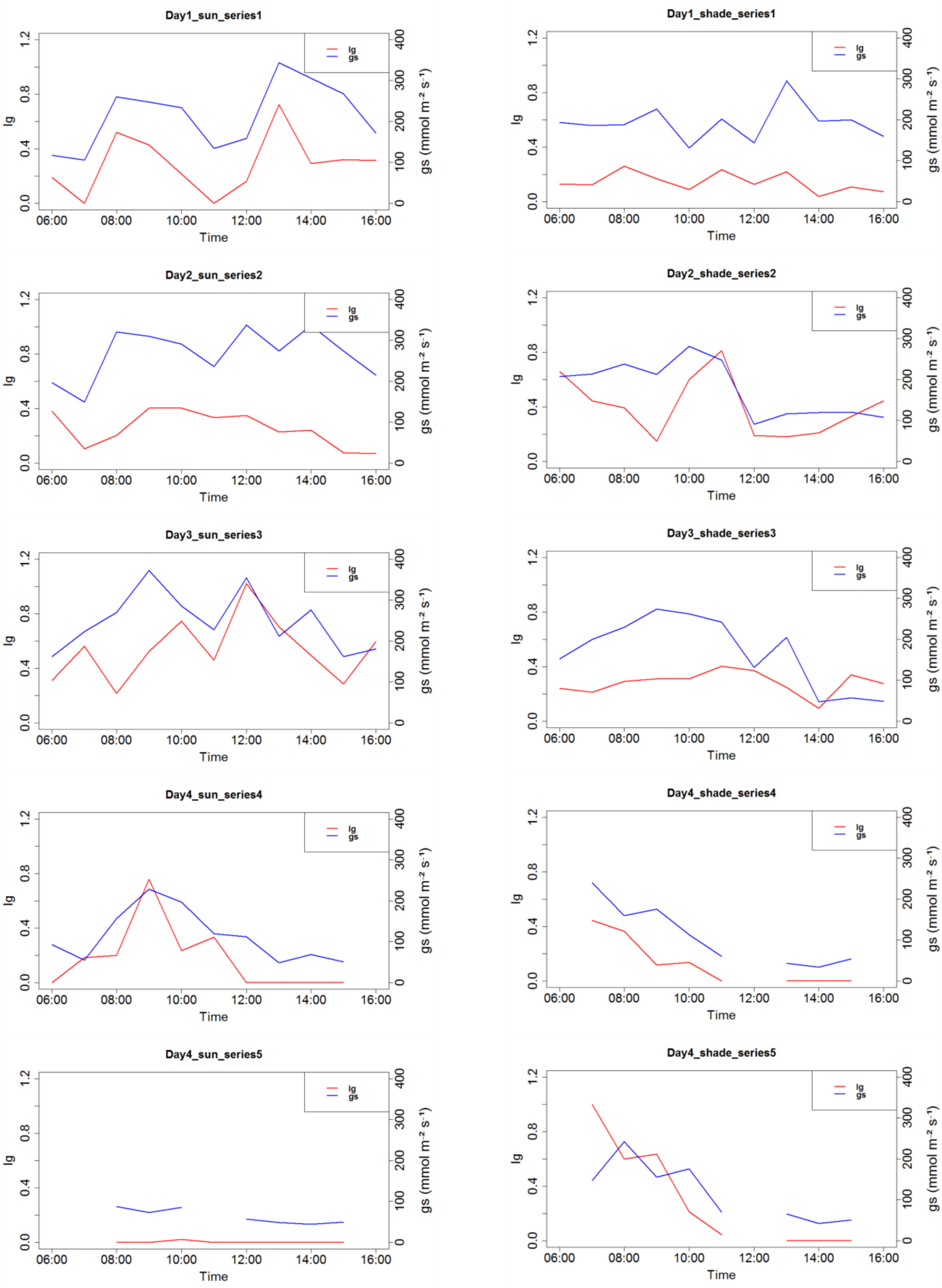


Fig. 5.3. Scatterplot of thermal index of relative stomatal conductance (I_g) and measured stomatal conductance (g_s) with associated linear regression line and confidence band of 95%.


Day1_sun_series1
Day1_shade_series1
Day2_sun_series2
Day2_shade_series2
Day3_sun_series3
Day3_shade_series3
Day4_sun_series4
Day4_shade_series4
Day4_sun_series5
Day4_shade_series5
lg
gs
Time
gs (mmol m⁻² s⁻¹)
06:00
08:00
10:00
12:00
14:00
16:00
0.0
0.4
0.8
1.2
0
100
200
300
400

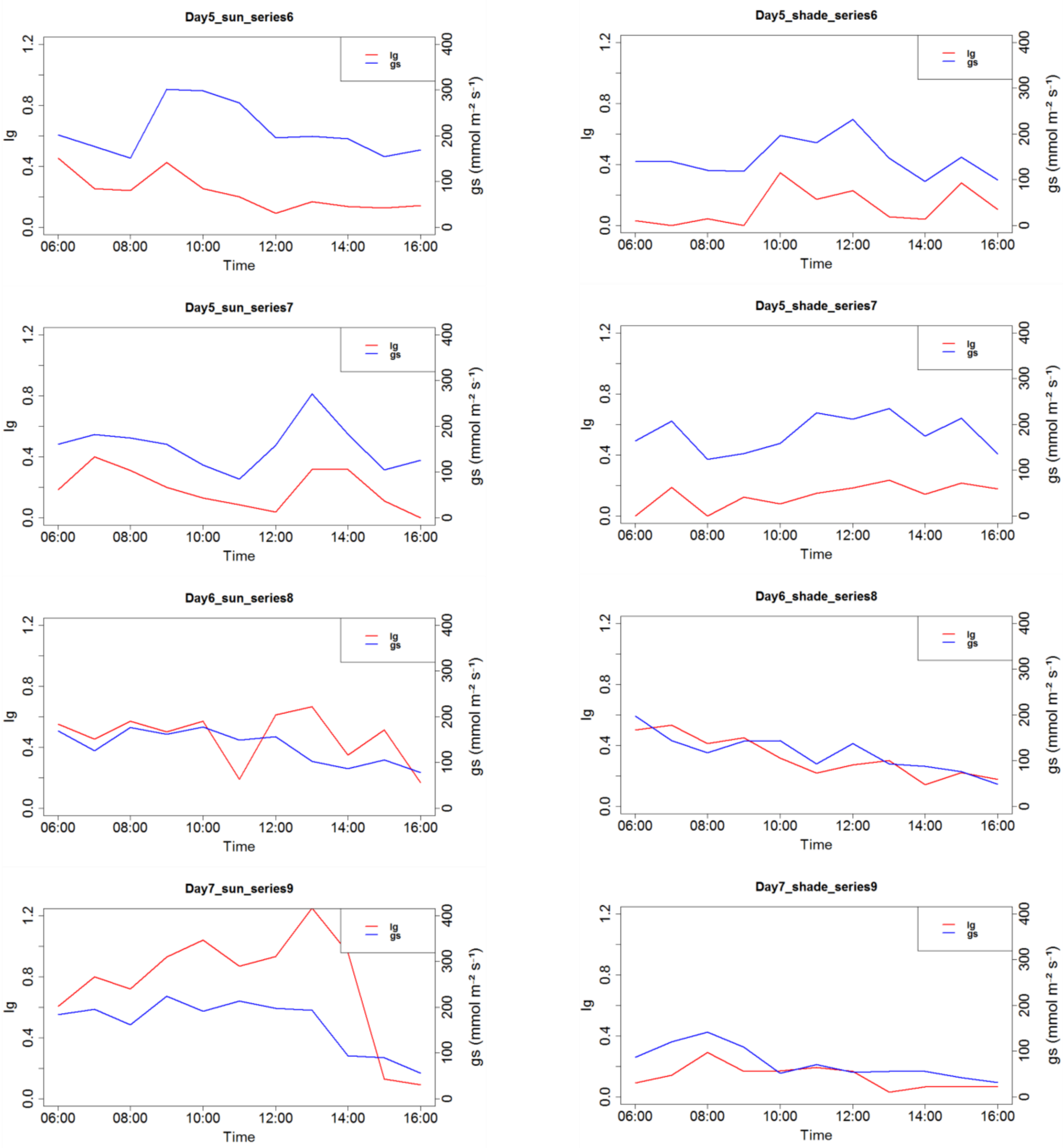


Fig. 5.4. Daily time series of I_g and g_s. Missing data are due to rainfall events.

5.4. Discussion

5.4.1. Accuracy of thermography methods and relationship to site meteorology

Experiments under diverse meteorological conditions and in a variety of different environmental contexts (i.e. *in situ*, *ex situ*, full sun and full shade) demonstrate an average correlation for all pooled data points between I_g derived from a thermal camera and stomatal conductance measured with a leaf porometer (Table 5.1, Fig. 5.3). Majority of individual series produced good correlations (r = >0.5) between methods used. In particular, there were a greater number of statistically significant correlations for measurements under shade conditions. Measurements in the sun have proven to be more representative of stomatal change than those in the shade, since there is a greater distinction between T_{leaf} and T_a for leaves with different g_s (Maes and Steppe, 2012; Grant et al., 2016). Nevertheless, in the coffee estate, the benefit from an increased temperature distinction between T_{leaf} and T_a may be offset by increased variability across individual sunlit leaf surfaces. More specifically, the lower standard deviation of both temperature and stomatal conductance measurements for shaded versus sunlit leaves may explain the greater significance observed in shade-related correlations.

Studies investigating relationships between I_g and g_s on grapevine (Jones et al., 2002; Fuentes et al., 2005; Grant et al., 2006, 2007) and various species of bean (Jones, 1999; Grant et al., 2006) show stronger correlations than those found here. However, all these studies use gradual changes of a specific physiological parameter (e.g. drought stress) to obtain responses from stomatal architecture over weekly or monthly time series. By contrast, Maes et al. (2016) recently published strong correlations over daily time series for both grapevine and kiwifruit. The less strong correlation between I_g and g_s for several of the daily time series in coffee suggests that potential errors associated with this method of thermographic measurements might have played a role. Principally, there is a large variation in T_{leaf} throughout the canopy under field conditions due to leaf orientation and shading (Maes and Steppe, 2012). Therefore, selecting leaves with identical characteristics is essential. Approaches such as taking the average of several leaves in the canopy (Maes et al., 2011) and separating the required pixels from background and non-leaf material have provided more robust estimates of I_g (e.g. Leinonen et al, 2006; Möller et al., 2007). Similarly, the accuracy of T_{wet} is heavily influenced by the time of wetting (Maes et al., 2016) and may also inadvertently influence the temperature and microclimate of other proximal/adjacent leaves (Jones et al., 2002; Grant et al., 2007). Mitigating some of the downfalls of obtaining accurate reference surface temperatures, several studies have proposed the use of artificial wet and dry reference surfaces (e.g. Meron et al., 2003; Pou et al., 2014; Grant et al., 2016). However, as demonstrated by Prashar and Jones (2014), there is room for improvement of these alternatives, owing largely to the very different energy balance of the artificial surfaces and leaf material. More recently, Maes et al. (2016) present a novel method for obtaining T_{wet}, which resulted in consecutively stronger correlations between I_g and g_s. The new approach uses an artificial reference surface, which consists of an object with similar dimensions, color and shape of an actual leaf that stays permanently wet.

Interestingly, meteorological conditions had a negligible influence on individual measurements of I_g and g_s (Table 5.2), as well as on the strength of the correlation between I_g and g_s. An impact of u on I_g and g_s was expected, since I_g has been shown to be independent of K_{in}, VPD, leaf inclination angle and albedo, but increases with increasing T_a and decreasing u (Maes and Steppe, 2012). Furthermore, several studies have illustrated the particular sensitivity of g_s in *C. arabica* to fluctuating VPD (Barros et al., 1997; DaMatta and Ramalho, 2006). The negligible effect of u on stomatal conductance measurements was further substantiated with the minimal statistical difference between correlations of I_g and g_s under controlled conditions in the laboratory (series 8 and 9 on days 6 and 7) and those *in situ* (Table 5.1). This may be attributed to the uncoupling of the leaf boundary layer to that of the bulk air. As leaves transpire, water vapour increases in the leaf vicinity, thereby decreasing the boundary layer conductance. When the plant canopy is poorly coupled to the atmosphere, such as in high density agroecosystems, transpiration becomes much more responsive to solar K_{in}, than VPD (DaMatta and Ramalho, 2006). Despite the insignificant influence of meteorological parameters on stomatal measurements, the average correlation coefficient (r=0.58, P= 1.77e-14) between all pooled points would suggest converting I_g to actual stomatal conductance (g_1), thereby ensuring values are comparable over variable G. However, the relationship of g_1 to g_s illustrates that incorporating other meteorological variables did not result in any better representations of g_s with a correlation coefficient of 0.57 (P= 7.27e-14) for all pooled data points. The fact that correlations were no more robust with g_1 than with I_g suggests there may be a degree of error associated with the methodology and in the calculation of r_{aV}. For instance, these relationships are based on detailed leaf level measurements, though T_a and RH are measured at the canopy level, thereby providing a degree of dissociation between the variables. Similarly, resistance to vapour transport in the leaf boundary layer depends on the leaf characteristic dimension as well as on u. In practice, the flow of air in the leaf boundary layer is often a combination of laminar and turbulent, and the coupling with canopy architecture may make the quantification of resistance at leaf level challenging (Jones, 2014). In addition, this boundary layer airflow may vary considerably from wind speed measured at a nearby station (40 km), adding further error to the calculation of resistance. Therefore, given that no microclimatic measurements are required for calculating I_g and results are comparable, if not better than g_1, makes I_g a very attractive parameter for estimating stomatal conductance.

5.4.2. Implications for coffee plantation management and climate smart agriculture

As a result of climate variability and change, there has been a strong focus on shading and agroforestry as a measure of crop protection in *C. arabica* (Lin, 2010), particularly under sub-optimal conditions (van Kanten & Vaast, 2006). Multistrata shaded coffee systems are common in E-Africa and provide a number of benefits to the farmer and environment, including the recycling of nutrients and soil organic matter sustenance, improved coffee quality, increased biodiversity and livelihood security (Vaast et al., 2006; Lin, 2010; Jha and Dick, 2010). However, the common notions of beneficial cropping systems are now being reassessed (Bertrand et al., 2016). The impacts of climate change on coffee may vary depending on the environment/system considered and variables such as shade, altitude and sunlight may either ameliorate or exacerbate the problem (Bertrand et al., 2016). As found in previous research, the rise in night time temperatures from increased shading and the effects on coffee crop physiology and production have not been addressed completely (Craparo et al., (a) unpublished). Recent studies have shown how rapidly advancing night time temperatures are forcing the highly niche-specific thresholds of *C. arabica*, resulting in a decline in yields in Tanzania (Craparo et al., 2015), as well as advancing phenological phases (Craparo et al., (b) unpublished). Similar rising trends in T_{min} have been recorded for other major *C. arabica* producing regions such as Brazil, Costa Rica, Colombia and Ethiopia (Quintana-gomez, 1999; Pounds et al., 2006; de los Milagros Skansi et al., 2013; Mekasha et al., 2014).

Considering these trends, the ability to gain rapid insights to the coffee plant's functioning or suitability in a particular environment would be highly beneficial, especially considering heterogeneous planting systems. These data provide novel primary groundwork to achieve these objectives for *C. arabica*. The method could be used to provide a rapid estimation of microclimatic effects on the plant; for different levels of shading or variations in altitude. Furthermore, the response of different varieties within these settings could also be quantified. The fact that the instrument and methodology is sensitive enough to quantify stomatal changes over a high temporal resolution (hourly), ensures that the stomatal response of the plant to large environmental changes such as drought, extreme minima or maxima, or stress caused by pests and disease, can be identified. In order to advance this protocol for use at the canopy- or plantation-scale on coffee, the study emphasizes several important findings: i) the method is able to account for highly variable meteorology, without needing to incorporate other meteorological parameters, ii) due to lower standard deviations of both T_{leaf} and g_s, measurements in the shade may be slightly more accurate than those in the sun, iii) there is considerable stomatal variability throughout the day, even within a single leaf, therefore measurements should be taken at least twice a day as opposed to the "typical" single daily measurement, iv) it is proposed that using artificial reference surfaces with identical characteristics to the leaf, such as those developed by Maes et al. (2016), will contribute to further accuracy, and v) novel techniques for obtaining reference surface temperatures which are representative of the whole canopy/plantation are required for *C. arabica's* highly variable canopy.

5.5. Conclusion

With high temporal resolution measurements, this study demonstrates for the first time the success of using thermography to estimate stomatal conductance of *C. arabica in situ*. Thermal indices and stomatal conductance measurements approximated one another over highly variable daily time series, with an average correlation of r=0.58 for all data points. Despite substantial variability in the micrometeorology, u and VPD had a negligible effect on individual I_g and g_s measurements, as well as on the relationship between these two parameters. The similar level of correlation from parameters in the meteorologically controlled environment substantiates these findings. Furthermore, even when accounting for variable boundary layer conductance by converting I_g to absolute stomatal conductance (g_1), these values were no better correlated to g_s than when using I_g. Based on these data, it is concluded that stomatal conductance of *C. arabica* may be estimated with thermography and limited meteorological data. This method would be best suited for comparative studies, screening or trend analysis where absolute values are not required. The technique could accelerate research on coffee and climate responses and would be particularly useful in quantifying the suitability of different coffee varieties under heterogenous cropping systems. There would be considerable merit in advancing the protocol in order to more accurately represent canopy or plantation-level measurements for a comprehensive and fast identification of stress, thereby assisting with climate change planning and site-specific adaptation.

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CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1. Introduction

This thesis investigates the interaction between atmospheric variables and different physiological responses of *C. arabica* over several spatio-temporal scales. For the first time in coffee physiology research, this study provides essential time series evidence of the impact of climate change on *C. arabica* [Craparo et al., 2015 (Chapter 2)]. Increasing minimum, or night time temperatures are shown to be a principal constraint, not only for coffee yields [Craparo et al., 2015 (Chapters 2 and 3)], but also for the plant's phenophases (Chapter 4). Importantly, current growing-systems discourse is brought into question, as the influence of "strictly" beneficial agroecological parameters such as shade may also induce unintended consequences on the meso- and microclimate, and subsequently on yield (Chapter 3). Finally, a novel sensing method is introduced which may be used to rapidly quantify the effect of different agroecological systems on coffee physiology, thereby assisting with the evaluation and improvement of climate change adaptation and planning practices (Chapter 5).

Utilizing long-term macroclimatic data, Chapter 2 illustrated how rapidly rising night time temperatures seem to have a profound impact on *C. arabica* yields. The study addresses an important gap in coffee research and provides the industry with tangible evidence that the impact on coffee yields is current and not just a future threat. In contrast to previous studies, the emphasis is not on extreme minima or maxima, but rather the diminishing suitable or optimal growing environment. As such, attention is also drawn to other global *C. arabica* growing regions with similar climatic trends. Using these data for forecasting, a biologically-based model was built to predict future trends, suggesting *C. arabica* yields in Tanzania would drop to critically low levels by the year 2060. The forecast from this model is in accordance with literature using different methods [e.g. MaxEnt, (Ovalle et al., 2015); machine learning, (Bunn et al., 2015)] indicating a substantial loss of suitability for *C. arabica* in Tanzania, as well as other global areas.

Addressing several limitations from the macroclimatic study (Chapter 2), these parameters were investigated at the meso- and microclimatic scale, now incorporating variability in crop management systems (Chapter 3). Using an altitude gradient as a proxy for climate change, based on the climate-analogue concept (Ramírez-Villegas et al., 2011), this study reinforces the findings from Chapter 2; with temperatures, and particularly minimum temperatures as a key driver for plant yield. Likewise, the variability in precipitation had a largely negligible effect on yields. Predicting the effect of climate change on *C. arabica* under different cropping systems is associated with uncertainty (Bertrand et al., 2016). Nevertheless, it is generally accepted that shading/agroforestry systems provide a positive influence on coffee physiology (Vaast et al., 2006; Lin, 2010; Jha and Dick, 2010). However, as demonstrated from this analysis, increased shade percentage may result in increased minimum temperatures and therefore a potential loss in yield. Much of the effects of shade trees on the micro-climate will depend on tree types, sizes, distribution, season, landscape and prevailing macro-climatic conditions. Thus, as suggested by Bertrand et al. (2016), the impacts of climate change on coffee vary depending on the environment considered and several variables (shade, altitude, sunlight) may either improve, or exacerbate the problem. The microclimatic dynamics described here and subsequent impact on yield, is therefore a key finding for the rapidly evolving field of coffee ecophysiology. Fundamentally, these results may help guide future (particularly agroforestry) research to better understand this dynamic for successful climate change adaptation strategies.

As temperatures reach unprecedented levels, the influence on plant phenophases becomes more substantial (Jung et al., 2016). Once again, night time temperatures surface as a principal element in Chapter 4, where they are shown to have a superseding effect on the timing of harvest. Intrinsically linked to yield as well as coffee quality (Pezzopane et al., 2012), the importance of this variable becomes immediately evident considering future change scenarios. This is of particular concern, since majority of the studied blocks had not yet even reached a mean night time temperature of 18°C. Phenological changes which advance the harvest date by several weeks may therefore have considerable logistical and financial implications for the farmer.

Thus far, this thesis represents a glimpse of the interaction between changing climate and *C. arabica*. However, if adaptation to climate change is ever to be effective, there needs to be a much faster method to quantify the influence of crop management and agroecological settings (and the underlying individual parameters) on plant performance *in situ*. Ultimately, it would require an understanding and quantification of the dynamics observed in previous chapters of this thesis, but at the leaf or canopy level and on a much shorter time series. These pressing terms encouraged the final chapter of this research, which for the first time, introduced the plausibility of using thermography on coffee. Unlike traditional methods which quantify plant functioning or status by using the stomata or other signals such as gas exchange and fluorescence, thermography can be applied at several scales (leaf, canopy, block or estate) and does not require contact with the plant (Costa et al., 2013). As demonstrated in Chapter 5, the most valuable feature of this technique is that the plant's status could be quantified over highly variable meteorological and cropping systems (full shade, full sun, *in situ* and *ex situ*), in a very short space of time. The novelty of this work therefore not only lies in the results, but also the methodology which contributed to advancing this protocol to be used effectively at the canopy or plantation level. With improved sensing technology as well as methodologies (e.g. Maes et al., 2016), thermography could be a critical tool not only for agroforestry and climate change adaptation planning, but also for plantation mangers to gain rapid insights to the plant's status.

6.2. Limitations and uncertainties

A common trend throughout this thesis is a preference for lower temperatures (<19°C) than what are currently suggested for *C. arabica* (<21°C) (Alègre, 1959). As demonstrated, these limits were found to be applicable not only for yield and production, but also for phenological aspects (Chapters 2, 3, 4). Importantly, these findings are all based on data using traditional *C. arabica* varieties. By contrast, newer developed cultivars, particularly those bred for higher yields and temperature suitability (e.g. Obatã IAC 1669-20, F1 hybrids), have been shown to withstand supra-optimal temperatures (Camargo, 2010; Martins et al., 2016). However, many of the cultivars are hybrids of *C. arabica* and *C. canephora* (arabusta), or are the result of backcrossing with an arabusta (cv. Icatu) and therefore may lack the quality of traditional varieties. Furthermore, breeding of improved varieties takes several years and is particularly focussed on developing pest, disease and drought tolerant traits (van der Vossen et al., 2015). Therefore, although the use of traditional varieties is a clear limitation of this thesis, they are not yet deprecated and are currently farmed throughout the majority of East Africa.

A further limitation of this thesis is the challenge of minimizing "noise" from other biotic and abiotic parameters in the field. Although controls were established in order to minimize the influence from different agricultural inputs, soil varieties and pest and disease pressure, these data are all from active farms with natural variability. As such, studies based on *ex situ* experiments have the ability to exercise a degree of control on these other variables, thereby potentially obtaining a more accurate response.

Recently, Martins et al. (2016) show how higher concentrations of CO_2 have mitigated the negative impacts of temperature stress, mostly by the increase of several protective molecules, antioxidant enzymes and the upregulated expression of some genes. Unfortunately, fluctuating concentrations of CO_2 could not be incorporated in the forecasting methods of this thesis. Although the study by Martins et al. (2016) was based on newer hybrid cultivars (Icatu), it still strongly suggests that as a result of increasing CO_2, the impact of future climate change on *C. arabica* may not be as severe as forecasted in this work.

This thesis represents an understanding of the response of *C. arabica* to environmental forcing's over several different scales. Extended research efforts are required to quantify the influence of climate change on this species in other global regions. Further in-depth analyses of the interactions and influence of each cropping system on the plant is essential, considering the rapidly changing growing environments worldwide. In addition, the synergies and trade-offs with other dynamics such as climate change mitigation, ecosystems services and livelihood security need to be incorporated in this system. As demonstrated, new sensing methods and technologies may add considerable value to understanding this dynamic, though there is still substantial room for improvement. In particular, there would be merit in advancing the reliability of the protocol for canopy- and farm- level measurements.

6.3. Closing remarks

In some respects, we are still in the infant stages of understanding the vegetal world, but it is hoped that the interactions observed in this thesis are only surface level, and that the plant, through its complex and brilliant functioning system, is able to adapt to changes in ways not yet discovered. For it was Charles Darwin who boldly quoted in his autobiography, "It has always pleased me to exalt plants in the scale of organised beings" and further reinforced it in the fundamental *The Power of Movement in Plants*, published in 1880.

There has been a progressive shift in thinking as well as understanding of plants since this time. We now acknowledge the complexity of a plants' sensing and communicative system, to the point where intelligence is considered. Climate change has provided further impetus for innovation. Research has shown that the arabica species is not suited for centralized variety development and global dissemination. Rather, successful cultivation lies in inspired agroecological design and breeding tailored to unique pockets on local and regional levels. Perhaps, in future, we may not only be able to maintain, manipulate and increase plant yields, but also translate biological adaptation concepts to innovations that will help human society adapt to environmental changes and shocks.

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Supplementary images

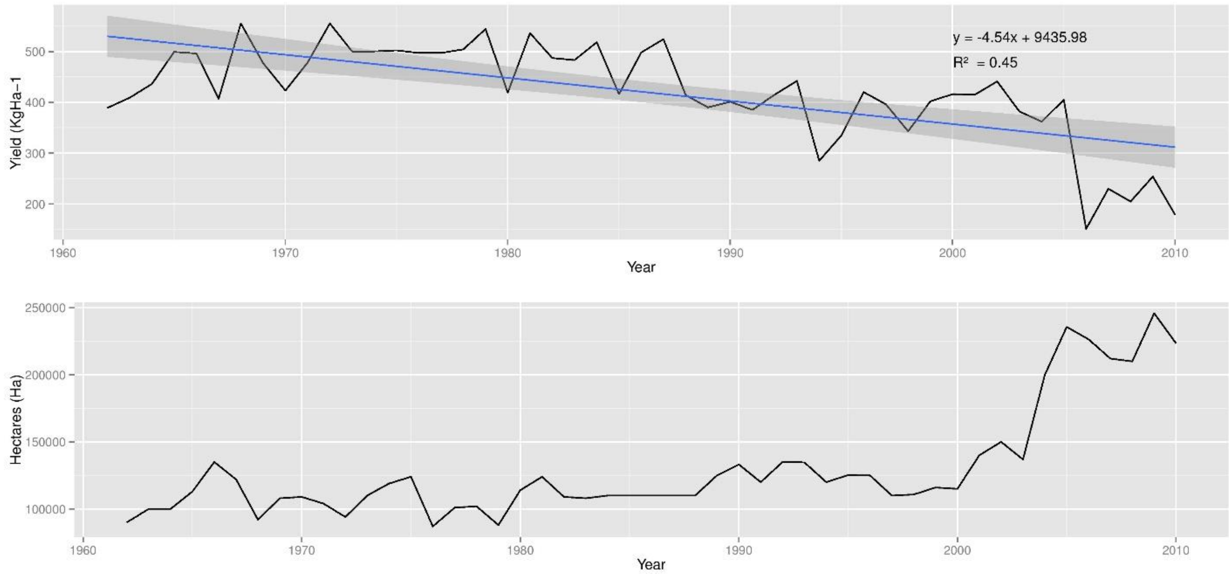

Fig. SI 2.1. Upper: trend of FAOSTAT production data corrected by cultivated area for the period 1962-2010. Lower: cultivated area, 1962-2010.

Selected media articles featuring research

Broadcast

CNBC Africa. Why coffee drinkers should be concerned. 29 April 2015.

Grossman, D. *NPR Radio*. How climate change is threatening Tanzania's coffee growers. 05 January 2017.

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