The past and future climatic suitability of arabica coffee (Coffea arabica L.) in East Africa.

RIDLEY, FRANCES,VICTORIA

The past and future climatic suitability of arabica coffee (*Coffea arabica* L.) in East Africa.

Frances Victoria Ridley

Department of Biological and Biomedical Sciences

University of Durham

Submitted in accordance with the requirements for a Master of Science by Research

Declaration of Copyright

I confirm that no part of the material presented in this thesis has previously been submitted by me or any other person for a degree in this or any other university. In all cases, where it is relevant, material from the work of others has been acknowledged.

Frances Victoria Ridley

Department of Biological and Biomedical Sciences
University of Durham

September 2010

Abstract

Coffea arabica (arabica coffee) is a socially and economically important commodity crop in countries throughout East Africa. The distribution and productivity of coffee is dependent upon climate, the environment, and socio-economic factors. Previous studies involving a wide range of plant and animal species have shown that climatic changes affect species distributions. Global circulation models suggest climatic change over the next century, and predict warmer temperatures, and increasingly variable precipitation in East Africa. Whilst several studies have modelled the potential impacts of future climatic change on global food crops, there is a lack of information on the potential suitability and likely productivity of arabica coffee in East Africa. Using information from previous studies this study suggested optimal and tolerable climatic thresholds of mean annual temperature, and total precipitation, for arabica coffee. Using a bioclimatic envelope model, the past, present, and future areas of climatic suitability of arabica coffee were determined in eight East African countries. A declining trend in the number of optimal and tolerable locations was identified over the past forty years in all eight countries. Using modelled future temperatures and precipitation from a range of global circulation models, it was shown that the number of optimal coffee locations will continue to decline over the next century. The number of future tolerable locations did not decline greatly, and increased in some regions. Correlating seasonal and mean annual temperatures and precipitation, with annual country-level yields from the past forty years, showed that some of the variance in yield could be explained by changes in temperature and precipitation. Socio-economic factors are of importance in determining arabica coffee productivity and the negative effects of future climatic changes may be mitigated through a range of management options.

Acknowledgements

I would like to express my thanks and appreciation to Dr Ralf Ohlemüller and Professor Brian Huntley for their support and guidance throughout this project. I thank Dr Yvonne Collingham for providing access to climatic data, Dr Cheryl McEwan for advice, and Wolfgang Weinmann at Cafédirect for information about the AdapCC project.

Thank you to all my friends, and colleagues at Student Community Action for your continual support and belief in me. Most of all though, thank you to my family, for your encouragement, support, and interest that you've taken in my work – I've done it; another little bean-bag on the arm race completed! Finally, to Philip: I don't think I would have embarked on this without you, you've got a lot to answer for!

CONTENTS

Chapter One: Introduction 1

1.1 Climatic Change, Agriculture and East Africa 2

1.1.1 Socio-economic and climatic characteristics of the East African region 2

1.2 Coffee as a commodity........ 4

1.3 Aims and Research Questions 6

1.4 Thesis outline 7

Chapter 2: A review of the physiological requirements of Coffea arabica........ 8

2.1 Origins of coffee........ 9

2.2 Morphology and physiology of C. arabica........ 9

2.3 Ecological requirements 10

2.3.1 Temperature........ 10

2.3.2 Water 11

2.3.3 Soil 13

2.3.4 Light........ 13

2.4 Coffee growing systems 13

Chapter 3: The bioclimatic envelope of Coffea arabica in eight East African countries 15

3.1 Introduction 16

3.2 Methods 17

3.2.1 The climatic trends and actual area of coffee harvested since 1961 17

3.2.2 The bioclimatic envelope of arabica coffee........ 19

3.2.3 Model evaluation 21

3.3 Results........ 22

3.3.1 Changing climatic trend, actual coffee land area harvested and the bioclimatic envelope of arabica coffee........ 22

3.3.2 The number of climatically suitable arabica coffee growing locations........ 26

3.3.3 The geographical distribution of coffee locations in eight East African countries 29

3.3.4 Predicted and actual C. arabica growing locations in Ethiopia........ 31

3.4 Discussion........ 35

3.4.1 Climatic variation and coffee distribution 35

3.4.2 The bioclimatic envelope of forest and garden coffee in Ethiopia 38

3.4.3 Non climatic factors affecting arabica coffee production in East Africa........ 39

3.4.4 Limitations........ 40

3.5 Conclusion 41

Chapter 4: The effect of climatic changes on arabica coffee yields in East African countries 43

4.1 Introduction 44

4.1.1 Climatic changes and crop yields 44

4.1.2 Empirical yield estimation models 44

4.2 Methods 45

4.2.1 Temporal patterns of arabica coffee yield in East Africa 45

4.2.2 Climatic correlates of arabica coffee yields in East Africa 46

4.3 Results 48

4.3.1 Temporal trends in the yields of arabica coffee in East Africa 48

4.3.3 Estimating yields of arabica coffee using mean climatic variables 55

4.4 Discussion 56

4.4.1 Climatic variation and arabica coffee yields 56

4.4.2 Non-climatic variables affecting yield 57

4.4.3 Methods of modelling crop yields 59

4.4.4 Limitations 60

4.5 Conclusion 61

Chapter 5: Future areas of climatic suitability for C. arabica in East Africa 63

5.1 Introduction 64

5.2 Methods 65

5.2.1 Future climatic variables 65

5.2.2 Identifying future climatically suitable areas 66

5.3 Results 67

5.3.1 Future climatic trends 67

5.3.2 Future climatic suitability of C. arabica in East Africa 71

5.3.3. Future climatic suitability of garden and forest coffee in Ethiopia 78

5.4 Discussion 79

5.4.1 The impact of changing climatic trends on arabica coffee production 79

5.4.2 Changes in the number of optimal and tolerable arabica coffee growing locations in East Africa 80

5.4.3 The future of garden and forest arabica coffee in Ethiopia 82

5.4.4 Limitations 83

5.5 Conclusion 85

Chapter 6: General Discussion 87

6.1 The effects of climatic changes on the distribution and production of arabica coffee in East Africa 88

6.1.1 Past and future climatic changes in East Africa 88
6.1.2 Climatic change and the suitability of arabica coffee in East Africa 89
6.2 Adaption and resilience to future climatic changes in East Africa..................... 90
6.2.1 Farmers perceptions of climatic vulnerability 90
6.2.2 Adaptation strategies for arabica coffee farmers....................................... 91
6.2.3 Water Management and heat stress 92
6.2.4 Options for diversification 94
6.3 Limitations and uncertainties in predicting the future suitability of arabica coffee in Eastern Africa... 95
6.4 Recommendation for future work 97
Chapter 7: Conclusions 99
Bibliography.. 102
Appendix... 113
Appendix One Climatic trends in East Africa from 1961-2002............................. 113
Appendix Two: The Spearman's Rho correlation coefficients between all climatic variables considered 115

TABLE OF FIGURES

Figure 1.1: The coffee producing nations of East Africa (EAFCA, 2008). 4

Figure 3.1: Climatic requirements for *Coffea arabica* for a) mean annual temperature and b) total annual precipitation. Red dotted lines represent the boundaries of conditions considered as optimal, and blue dotted lines represent the boundaries considered as tolerable. 18

Figure 3.2 a) A two-dimensional bioclimatic envelope for a species (Guisan & Zimmerman, 2000) b) The optimal bioclimatic envelope for *C. arabica* growth c) The tolerable bioclimatic envelope for *C. arabic*a growth. 20

Figure 3.3: Optimal and tolerable conditions for *C. arabica* in a 2-dimensional climate space (mean annual temperature, total annual precipitation), based upon the average 1990-1999 climatic conditions of all land grid cells of the eight East African countries investigated.24

Figure 3.4: Actual area of land harvested for arabica coffee within each country over time (FAO, 2009)... 25

Figure 3.5: Total number of optimal (blue) and tolerable (red) coffee growing locations in eight East African countries. 26

Figure 3.6: The number of optimal (blue) and tolerable (red) coffee growing locations in eight East African countries (n = total number of land grid cells in country) 28

Figure 3.7: The geographical distribution of optimal and tolerable coffee growing locations, based on decadal mean annual temperatures and total annual precipitation between 1961 and 2002. 30

Figure 3.8: Predicted and actual coffee growing locations in Ethiopia using (a) tolerable and (b) optimal climatic thresholds, based on 1990-99 climate averages........................ 31

Figure 3.9: The bioclimatic envelope of forest and garden coffee growing locations in Ethiopia 33

Figure 3.10: a) Mean temperature of the coldest month (MTCO) and mean temperature of the warmest month (MTWA) for coffee and non-coffee sites in Ethiopia. b) The average annual precipitation and actual/potential evapotranspiration (APET) of coffee and non-coffee sites in Ethiopia... 34

Figure 4.1: a) Mean annual yields of arabica coffee in all East African countries studied excluding Uganda, and b) annual yields of arabica coffee by country. Dotted lines indicate the upper and lower quartiles.. 49

Figure 4.2: Characteristics of annual coffee yield in relation to mean annual temperature and total precipitation in a 2D climate space. 52

Figure 5.1: Monthly and total annual precipitation for present day, 2020, 2050 and 2080 using two different greenhouse gas scenarios (A1B and A2), and three different global circulation models 69

Figure 5.2: Mean monthly and annual temperatures for present day, 2020, 2050 and 2080 using two different greenhouse gas scenarios (A1B and A2), and three different global circulation models 70

Figure 5.3: A 2D bioclimatic envelope of all land cells within East Africa, with the thresholds of optimal (red) and tolerable (blue) climatic thresholds for *C. arabica*. Climatic data is based

upon the mean results from three different GCMs, and under the A1B and A2 emissions scenario.. 72

Figure 5.4: The number of suitable optimal and tolerable *C. arabica* growing locations in recent decadal time-slices and in 2020, 2050 and 2080 predicted by three GCMs under the A1B and A2 emission scenarios. 73

Figure 5.5: The geographical distribution of climatically suitable locations for *C. arabica* in 2020, 2050 and 2080 (Pink= location predicted as suitable by one model, Blue= location predicated as suitable by two models and Green=location predicted as suitable by three models) 75

Figure 5.6: The percentage of current suitable *C. arabica* growing locations by country, which remain suitable in the future, calculated from the combined results of three GCMs. 76

Figure 5.7: The number of coffee growing locations identified as suitable, under optimal and tolerable temperature and precipitation thresholds, through time. Mean temperatures and precipitation, calculated from the output of three GCMs, were used to represent the future climate.. 77

Figure 5.8: The number of forest and garden coffee growing locations in Ethiopia under optimal and tolerable climatic conditions through time. Climatic conditions are calculated as a mean of the output from three GCMs. 78

LIST OF TABLES

Table 1.1: The ranking of East African countries based on the Human Development Indices Ranking 2006 (UNDP, 2008). 3

Table 1.2 : The total export value of coffee, and the contribution of coffee to the total agricultural export value in eight East African countries (FAO, 2009)........................... 5

Table 3.1: Trends in the average temperature, total precipitation, coffee area harvested, and number of optimal and tolerable coffee growing locations in eight East African countries between 1961 and 2002. 23

Table 3.2 Indicators of the performance of the bioclimatic model. a) The identification of true positive, false positive, true negative, and false negative indicators. b) The performance of the bioclimatic model when tolerable climatic thresholds are used. c) The performance of the bioclimatic model when optimal climatic thresholds are used. 32

Table 3.3: The bioclimatic envelope of actual Ethiopian coffee growing locations...... 35

Table 4.1: The seasons and coffee harvesting months of East African countries. (Red cells show the warmest and wettest season, blue cells show the coolest, driest season). (EAFCA, 2009)... 46

Table 4.2: Spearman's Rho Correlation Coefficients of annual and seasonal climatic variables and arabica coffee yields in East Africa. 54

Table 4.3: Explaining the variation of arabica coffee yields: the significance of seasonal and annual climatic variables 55

Table 4.4: The results of the stepwise model using yield as the dependant variable and seasonal and annual climatic variables as independent variables............................. 56

Chapter One

Introduction

1.1 Climatic Change, Agriculture and East Africa

Climatic change over the latter part of the 20th century is well documented and, since 1960, mean global temperatures have increased and precipitation has become increasingly variable, with extreme drought and flood events occurring with increased frequency (Parry *et al*., 2007; Funk *et al*., 2008). The rate of polar ice melt has increased and glaciers have retreated or disappeared altogether (Boko *et al*., 2007). Global circulation models (GCMs) are used to suggest future temperatures and precipitation, and generally they conclude that many regions of the world will become warmer with greater precipitation variation and more frequent climatic extremes (Boko *et al*., 2007; Doherty *et al*., 2010).

Agriculture will be directly and significantly affected by these future climatic changes (Brown and Funk, 2008). The growth, development and yield of agricultural crops are influenced by many climatic factors. Changes in temperature, precipitation regimes, frequency of extreme events, and atmospheric concentrations of CO_2 resulting from climatic change, will inevitably affect the production of agricultural crops (Tubiello *et al*., 2007). Higher temperatures may lengthen growing seasons, reduce soil moisture, alter plant development and product quality and affect crop pests and diseases (Downing, 1991).

Constructing models to predict crop responses to climatic change and identifying geographical regions most affected by future changes are required to aid adaptation strategies (Lobell *et al*., 2008). Without adaptation, many regions of the world will be affected by increased levels of hunger, flooding, drought and crop failure (Liu *et al*., 2008; Lobell *et al*., 2008; Thornton *et al*., 2009).

1.1.1 Socio-economic and climatic characteristics of the East African region

According to the United Nations Development Programme (UNDP), many of the world's poorest countries are found within East Africa (Table 1.1). Many East African households rely upon agriculture as a source of income as well as providing food for their families. Agricultural products contribute significantly to the export earnings of many East African countries and, on average, agriculture contributes 21% to African GDP, rising to as much as 70% in some African nations (Mendelsohn *et al*., 2000).

Table 1.1: The ranking of East African countries based on the Human Development Indices Ranking 2006 (UNDP, 2008).

Country	Poorest Country Ranking
Burundi	7th
Ethiopia	10th
Rwanda	14th
Zambia	16th
Malawi	17th
Uganda	23rd
Tanzania	27th
Kenya	35th

Malnutrition amongst East African populations is high, adult literacy rates and enrolment in secondary education are low, disease burdens the population, and regions are often hot and arid (Boko *et al*., 2007). Estimates for future population growth indicate a growing population in all areas of the region (UN Population Division, 2008). In some countries population is expected double from the present day by 2050. Such increases will intensify the pressure on natural resources in the region over the coming century.

The climate and topography of East Africa is diverse, ranging from humid tropical lowlands, to high and dry mountain plateaus. Temperatures in lowland plains are warm throughout the year (above 22°C), but decrease in mountainous areas away from the coast. Precipitation regimes in some parts of East Africa are bimodal, resulting in two wet seasons each year. The equator transcends East Africa, running through Uganda and Kenya (Fig. 1.1).

Several studies have highlighted that African ecosystems are highly vulnerable to changes in climate (Slingo, 2005; Parry *et al*., 2007; Schmidhuber and Tubiello, 2007; Ingram, 2008). Significant changes in rainfall patterns, both temporally and spatially, have been indentified in addition to rising temperatures in many areas (Boko *et al*. 2007). Over 75% of the glaciers on Mount Kilimanjaro in Tanzania (East Africa) have melted since 1912 (Kaser *et al*., 2004; Soini, 2005). An economic analysis of 9000 farmers in eleven African countries predicted falling farm revenues given future climatic change (Mertz *et al*., 2009). Climatic variability, poor infrastructure, economic poverty and low productivity are significant challenges for the East African region (Mertz *et al.*, 2009).

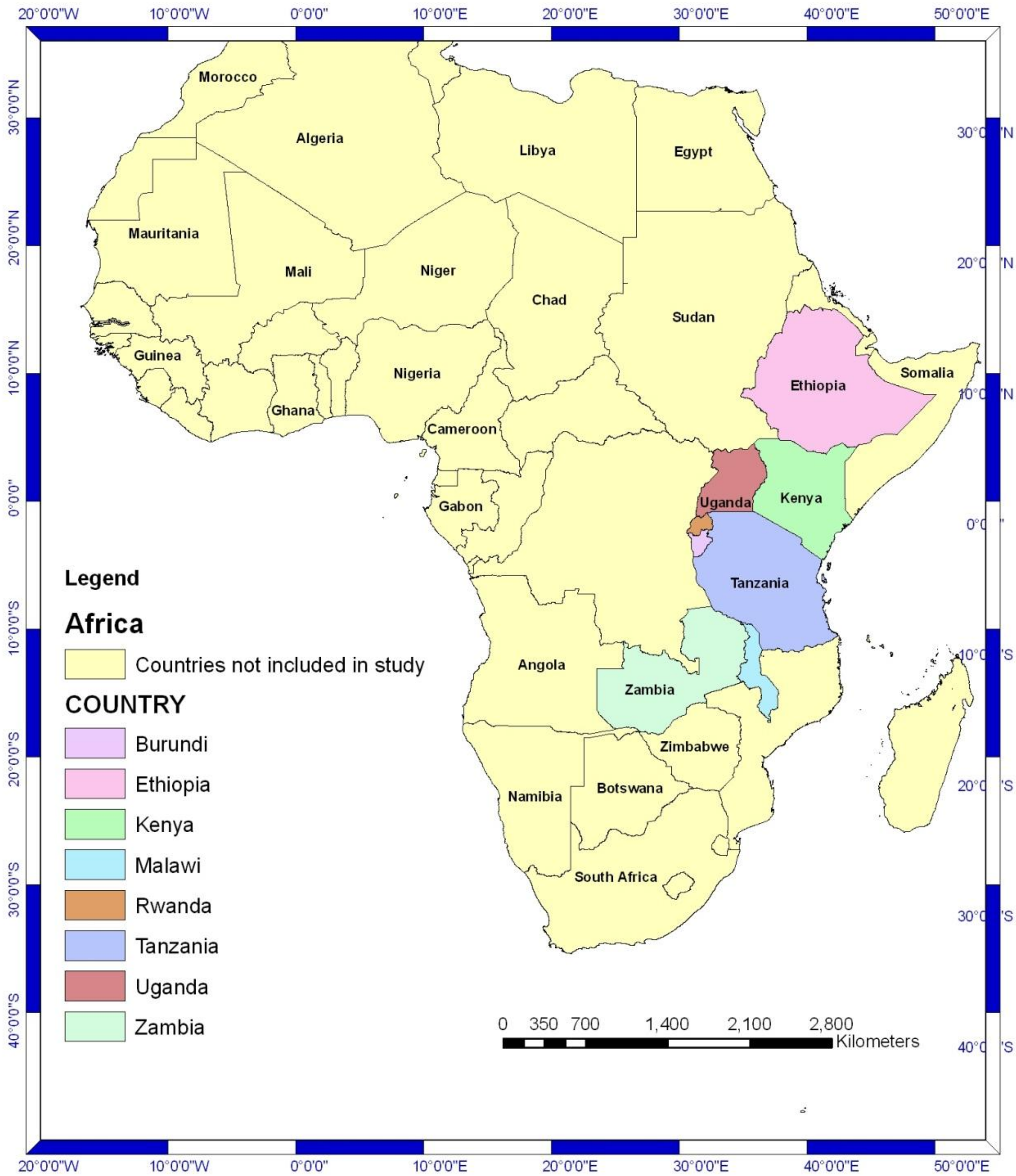


Fig 1.1: The coffee producing nations of East Africa (EAFCA, 2008).

1.2 Coffee as a commodity

Coffee is the second most highly traded commodity in the world after crude oil, making it an extremely valuable crop (Ghosray, 2010). For many countries in East Africa (Fig 1.1), coffee is an important agricultural commodity in terms of economic value, and several of the countries in East Africa are amongst the largest coffee exporting nations in the world (FAO, 2009). In Burundi, coffee accounts for 83% (Table 1.2) of the total value of agricultural exports, whilst in Ethiopia, the indigenous home of *Coffea arabica L.* (arabica coffee), 15 million people are dependent upon the coffee industry (Petit, 2007; Labouisse *et al*., 2008). In Ethiopia, arabica coffee is economically important, but coffee cultivation and consumption is deep rooted in the country's identity and culture (Labouisse *et al*, 2008). The coffee industry is important both socially and economically to the entire East Africa region, employing millions of people and providing income to support families and livelihoods across the region.

Table 1.2: The total export value of coffee, and the contribution of coffee to the total agricultural export value in eight East African countries (FAO, 2009)

Country	2007 Export Value of Coffee (US$ 000)	Contribution of Coffee to total Agricultural Export (%)
Burundi	46,895	83.9
Rwanda	32,460	42.7
Ethiopia	416,783	40.6
Uganda	226,966	33.7
Tanzania	113,064	16.7
Kenya	416,783	7.2
Zambia	8,756	3.3
Malawi	3,388	0.4

In Ethiopia, the indigenous home of arabica coffee, the species is of great ecological importance (Petit, 2007; Labouisse *et al*., 2008). Wild coffee is still harvested from highland forests, which are home to highly diverse coffee populations, and are of international importance. They provide a rich gene pool, which has the potential to be used for breeding new coffee varieties (Senbeta and Denich, 2006; Schmitt *et al*., 2009). Forest coffee is important in regional land-use, and deforestation could result in genetic erosion and a decline in land fertility (Soini, 2005; Labouisse *et al*., 2008; Tucker *et al*., 2010). Forest coffee is therefore an important ecological commodity in Ethiopia (Petit, 2007; Labouisse *et al*., 2008).

Concerns over the future suitability of commodity crops in the region have arisen, and Downing (1991) suggested that as the climate becomes warmer in Kenya, many of the tea plantations would become uneconomical. Assessing how future climatic change will affect coffee distribution and yields is critical in assessing the sustainability of the industry in the region. Studies from other areas of the world have concluded that coffee is a climatically sensitive crop, and that changes in the future climate could negatively affect coffee production (Gay *et al*., 2006). To increase the effectiveness of adaptation processes, and to utilise the financial resources available from aid and donor organisations, an understanding of crop responses to climatic variables, and regional studies highlighting areas most at risk from climatic change are required (Slingo *et al*., 2005; Lobell *et al*., 2008; Thornton *et al*., 2009). Despite this few studies have investigated the impact of climatic change on coffee production. Research is needed to assess how regional changes in temperature and precipitation will affect the suitability and productivity of arabica coffee in East Africa.

1.3 Aims and Research Questions

The aims of this study were to: investigate the trends of recent-past climatic change and the affect on *Coffea arabica* distribution; establish relationships between climatic variables and arabica coffee yield; and, identify current arabica coffee growing regions in East Africa that are at risk from future climatic change. The outcome of such research should be used to inform future adaptation and mitigation strategies, and to improve the resilience of local East African coffee growing communities to future climatic changes. The study aimed to identify regions at a high spatial resolution, rather than investigating the impacts of climatic change on single countries, or communities. To do these three questions were investigated.

Q1. What are the present bioclimatic limits of *C. arabica* distribution in East Africa?

Arabica coffee is a climatically sensitive species, and optimal and tolerable climatic thresholds were identified through a literature search. Using a bioclimatic envelope modelling approach the optimal and tolerable climate conditions for *C. arabica* in eastern Africa were identified. Model predictions were evaluated using data on actual arabica coffee distribution in Ethiopia.

Q2. How has past climatic change affected arabica coffee yields in East Africa?

Using climatic data and arabica coffee yield information from 1961-2002, trends and relationships between climatic variables and resulting yields were identified. This was used to determine the primary climatic factors that affect arabica coffee yields and, establish a multiple regression based model to predict future arabica coffee yields, based upon climatic variables.

Q3. Which areas currently suitable for arabica coffee production are most likely to be affected by future climatic change?

Predictions from global circulation models suggest that changes in future precipitation patterns and temperatures should be expected in eastern Africa. These changes could affect the spatial distribution of areas climatically suitable for arabica coffee, and many regions could become unsuitable. This study identifies arabica coffee growing regions that are likely to be most affected by future climatic changes, and this information can be used to will help determine appropriate mitigation and adaptation strategies for these communities.

1.4 Thesis outline

To begin, in Chapter Two, this thesis reviews the literature on coffee production and physiology to identify important optimal and tolerable climatic conditions for successful cultivation of *C arabica*. Using these thresholds, current arabica coffee producing regions in eight East African countries are identified using a bioclimatic envelope modelling approach (Chapter Three). Using climate and yield data from the past 61 years, Chapter Four explores the relationships between climatic variables and arabica coffee yields using a multiple linear regression model. Chapter Five uses future climatic data from three global circulation models, to determine future regions suitable for arabica coffee production. The findings from this study and the wider implications are explored in Chapters Six and Seven.

Chapter 2

A review of the physiological requirements *of Coffea arabica*

2.1 Origins of coffee

The genus *Coffea* is part of the Rubiacea family. There are a number of species, but only *Coffea arabica L.* (arabica) and *Coffea canerphora* (robusta) are economically and commercially significant (Wrigley, 1988; DaMatta, 2004). *C. arabica* is indigenous to the forested highlands of Ethiopia, and was introduced from Africa to the Yemen in the early 14^{th} century (Wrigley, 1995; Teketay, 1999). Arabica coffee was introduced to India, and then Java. In 1706, a plant from Java was introduced to the Amsterdam Botanical Gardens. Almost all commercially grown arabica coffee in the New World can be traced to this single tree, therefore the genetic base of commercial *C. arabica* is very narrow (Wrigley, 1995). This has been confirmed by the results of DNA testing on 40 varieties of arabica coffee (Diniz *et al*., 2005). Genetic heterogeneity is greatest within the wild arabica coffee populations of the Afromontane coffee forests of Ethiopia (Gole *et al*., 2008; Labouisse *et al*., 2008).

The primary coffee producing regions of the world are Latin America, South East Asia and East Africa. In Africa, coffee contributes greatly to the export earnings of Burundi, Ethiopia, Kenya, Malawi, Rwanda, Tanzania, Uganda and Zambia. Arabica coffee is primarily grown in these countries, except in Uganda where 96% of coffee produced is of the Robusta variety (EAFCA, 2008). The focus of this study is on the climatic suitability for arabica coffee production as this is the more dominant species in East Africa, and the species has a greater economic value (Ghoshray, 2010).

2.2 Morphology and physiology of *C. arabica*

Arabica coffee is a perennial, C_3 understory woody species, ranging in size from small shrubs to 16m tall trees (Wrigley, 1988). It is an evergreen plant, although some species will lose their leaves at the start of the dry season, while others maintain leaves for three years or more (Wrigley, 1995). Leaf morphology is variable and can range from one - 40cm in length, and from yellowish, to dark green in colour (Wrigley, 1995). The fruit of coffee trees, known as coffee cherries or beans, range in size and colour depending upon the species and stage of maturity (Wrigley, 1995). Although self-fertilising, *C. arabica* fertilisation benefits from insect pollinators such as bees (Klien *et al*., 2003).

The arabica coffee plant enters into a reproductive stage in its third year of life, but plants do not reach full maturity until their fifth or sixth year (Cambrony, 1992). Wild coffee plants found in the montane forests of Ethiopia can reach 100 years or more, but generally arabica plants remain economically productive for around ten years (Teketay, 1999).

Coffee grows throughout the year, but growth and development varies continuously due to temperatures, rainfall and day length (Wrigley, 1988). In equatorial regions there may be one, or two rainy seasons each year, respectively producing one or two blossoming and fruiting stages each year. Therefore, in some countries there are two separate coffee harvests each year (Cannell, 1985).

2.3 Ecological requirements

Local environmental conditions are important for the successful production of coffee. If mean temperatures are too high, biological and economic productivity can be negatively affected (Cannell, 1985). The total amount of precipitation in an area each year will also impact productivity by affecting water availability. The following section reviews literary sources and results of previous studies, to identify optimal and tolerable environmental conditions for arabica coffee production.

2.3.1 Temperature

The optimal temperature for arabica coffee growth is between 15°C and 24°C (Willson, 1985; Gay *et al*., 2006), although several sources give more specific ranges. Alègre (1959) concludes that favourable mean temperatures for coffee plant growth lie between 16°C and 23°C, with the optimum from 18°C to 21°C (Barros, 1997; DaMatta, 2004; Lin, 2007). Descroix and Snoeck (2004) state that the optimum mean night time temperature is 18°C, and the optimum daytime temperature is 22°C. Teketay (1999) describes arabica coffee as thriving in areas tempered by altitude, and between 18°C and 24°C. Descroix and Snoeck suggest that the tolerated extremes for arabica coffee extend to a 15ºC minimum during the night, and between 25°C - 30°C during the day (Descroix and Snoeck, 2004).

High or low temperatures can significantly damage the productivity of arabica coffee plants in a number of ways:

High temperatures:

1. Temperatures greater than 23°C can accelerate the development and ripening of fruit leading to loss of quality (Carmargo, 1985, cited from: DaMatta, 2004).

2. The photosynthetic rate is reduced at temperatures above 25ºC (Willson, 1985; Descroix and Snoeck, 2004).
3. Exposure to temperatures greater than 30ºC depresses growth. High temperatures can result in abnormalities within the leaves, stems, flowers or plants, reducing coffee yields (Franco, 1958, cited from: DaMatta, 2004; Descroix and Snoeck, 2004; Eakin *et al*., 2009).

Low temperatures:

1. Low temperatures cause the discoloration of leaves and exposure to temperatures below 4°C can result in serious lesions on both the leaves and coffee cherries (Descroix and Snoeck, 2004).
2. Exposure to temperatures below -2°C for durations of 6 hours or more can cause serious damage to leaves and death of the plant (Descroix and Snoeck, 2004).

Arabica coffee trees are severely damaged by frost, and are therefore not suited to regions that experience sub-zero temperatures, even for short periods of time (Wrigley, 1985; Gay *et al*., 2006). Large changes in diurnal temperatures can affect yield and quality, and the maximum tolerance is a range of 19°C (Wrigley, 1985; Descroix and Snoeck, 2004).

In addition to the direct control on coffee growth, temperature has an indirect influence. For example, high and low temperature extremes increase the threat to coffee from pests and disease. High temperatures favour the development of Coffee Leaf Rust (*Hemileia vastatrix)* and fruit blight, while Coffee Berry Disease is more prominent in cool regions (Descroix and Snoeck, 2004).

Temperature is critical to the growth and development of arabica coffee and temperatures which are too high or too low can negatively affect the development, yield and quality of coffee.

2.3.2 Water

Water availability is determined by total levels of precipitation and atmospheric humidity. Rainfall is the most restrictive factor in coffee growing regions, and both the total annual rainfall, and monthly distributions of precipitation are important (Descroix and Snoeck, 2004). A soil water deficit decreases the biological and economic productivity of coffee, by lowering the quantity and quality of the yield (Gutierrez and Meinzer, 1994; DaMatta, 1997).

If the dry season is not prolonged, and soils have a high water retention capacity, coffee can be grown without irrigation in areas where total precipitation exceeds 1100mm a year (Blore, 1966, cited from Descroix and Snoeck, 2004). Although coffee can be viable in areas that receive between 800mm and 1000mm of precipitation a year, even if this is ideally distributed in time, overall productivity will be low (Descroix and Snoeck, 2004). For higher yields, more precipitation is required.

Optimal annual rainfall for arabica coffee lies within the range of 1200-1800mm (Alegre, 1959, cited from DaMatta, 2004; Wrigley, 1985; Descroix and Snoeck, 2004). According to Teketay (1999), arabica coffee can be grown in regions with annual rainfall of under 762mm, to well over 2540mm, although the best conditions are areas with annual rainfall of between 1524mm - 2286mm. In many coffee producing areas, total annual rainfall lies between 2500mm and 3000mm (Descroix and Snoeck, 2004), and, providing soils have good drainage properties, arabica coffee is productive. If total precipitation exceeds 3000mm, the region is usually less successful in producing economically viable coffee.

From both field observations and controlled irrigation experiments, it has been shown that arabica coffee requires a period of water shortage to trigger floral initiation (Alvium, 1960; Cannell, 1985; Crisosto, 1991; Cambrony, 1992; Gay *et al*., 2006). A dry season of 12 – 14 weeks is critical for the growth and development of arabica coffee, as it enables internal water stress to develop. Months in which rainfall is less than twice the monthly average temperature can be considered as ‘dry months’ (Descroix and Snoeck, 2004). When the rains occur, plants break out of dormancy, triggering blossoming and rapid shoot growth (Cannell, 1985; Wrigley, 1988). If the soil conditions are favourable, arabica coffee can withstand a dry season of up to six months (Descroix and Snoeck, 2004). In regions lacking a dry season, harvest periods are scattered throughout the year, and overall annual yields are low (Maestri and Barros, 1977, cited from DaMatta, 2004).

High relative humidity can reduce the water loss from the coffee plant and soil, and optimal atmospheric humidity is 60% for arabica coffee. Relative humidity above 85% can negatively affect the quality of coffee (Descroix and Snoeck, 2004). Cloud cover and mist increases the relative humidity, which is advantageous during the dry season

(Willson, 1985). Morning dew can also provide an additional water source, especially in mountainous regions (Descroix and Snoeck, 2004).

2.3.3 Soil

Coffee requires soil to have good drainage properties, but a high water holding capacity. Heavy clay soils are undesirable (Willson, 1985). Arabica coffee thrives in regions with deep, well drained loamy soils, with a slightly acidic pH and a good supply of humus and exchangeable bases, especially potassium (Wrigley, 1995). Soils with a depth of at least 1.2m are preferred (Cambrony, 1992; Descroix and Snoeck, 2004), as this decreases the likelihood that plants will become water stressed during the dry season (Willson, 1985). Coffee prefers soils that are slightly acidic (Willson, 1985).

2.3.4 Light

Coffee has evolved as a shade adapted species, because it is native to the forested Ethiopian highlands (Cannell, 1985; Descroix and Snoeck, 2004). The photosynthetic rate is more efficient in shade leaves (Cannell, 1985). In their native habitats, arabica plants produce few flowers, as floral initiation is light dependent. This limits the amount of fruit that a tree can produce. In high light intensities, arabica coffee trees produce greater number of flowers and thus cherries. As coffee cannot shed excess fruit, the tree becomes committed to filling these coffee beans, requiring inputs such as minerals and nutrients greater than can be sourced (Cannell, 1985).

2.4 Coffee growing systems

Coffee is cultivated in a diverse range of managements systems, from native and wild coffee forests in Ethiopia to large, modern plantations (Teketay, 1999; Petit, 2007; Lin and Richards, 2007; Gole *et al*., 2008). Within East Africa, the majority of coffee is produced by smallholder farmers who manage less than three hectares of land (Teketay, 1999; AdapCC, 2009). Smallholder, subsistence farms in Africa generally grow several different crop species. A farmer will feed their family from the land, and will sell any additional produce. Smallholder farms in East Africa are usually organic or have a very low input of fertilisers and insecticides. Most work is done by hand and manual labour, as technology and machinery is expensive and unavailable in many rural areas. The farms are rain-fed and do not usually have access to irrigation systems (AdapCC, 2009).

In Ethiopia, coffee farming systems can be divided into four categories: forest coffee, semi-forest coffee, garden coffee, and semi-modern plantations (Teketay 1999; Petit, 2007; Labouisse *et al*., 2008). Forest coffee plantations in Ethiopia are of significant importance, as they are the only location where wild populations of *C. arabica* are found (Teketay, 1999; Gole at al., 2008; Labouisse *et al*., 2008). When forests are unmanaged, but coffee is collected, they are recognised as forest-coffee systems (Teketay, 1999; Labouisee *et al*., 2008). Semi-forest systems are those that are partly managed by removing understorey shrubs and slashing weeds (Petit, 2007; Labouisee *et al*., 2008). Garden coffee is grown by smallholder farmers, often with the protection of several large shade trees, and intercropped with subsistence food crops (Petit, 2007; Labouisee *et al*., 2008). This is the most common form of coffee production in Ethiopia and Eastern Africa. Finally, coffee plantations are larger areas of land that have been specifically cleared for coffee growing activities. They are usually state owned and have higher levels of mechanisations and chemical inputs (Petit, 2007).

In summary, *C. arabica* is grown in regions throughout East Africa and contributes significantly to the economic and social development of the region, as a high value export crop (FAO, 2009). The species is climatically sensitive to high and low temperatures. Well-drained soils are required, but water needs to be available, and arabica coffee thrives in regions with total annual precipitation between 1000mm and 2500mm. A three month dry-season is needed, to initiate flowering. In Chapter Three, these tolerable and optimal climatic threshold conditions are used to determine regions within East Africa that are currently suitable for arabica coffee production.

Chapter 3

The bioclimatic envelope of *Coffea arabica* in eight East African countries

3.1 Introduction

A fundamental aspect of biogeography relates to the relationships between macroclimate variables and species distributions (Prentice *et al*., 1992; Huntley *et al*., 1995). Available water, air temperatures, humidity and atmospheric composition are fundamental to the growth and development of plants (Osborne *et al*., 2007). Quaternary studies show that changes in climatic variables affect a species' range and distribution (Woodward, 1987). At large spatial scales, the dominating factor affecting plant species distributions are macroclimate factors. Biotic interactions impact upon distributions at the microscale, but major patterns at spatial resolutions of above ca. $10km^2$ are largely related to macroclimate variables (Huntley *et al*., 1995; Pearson and Dawson, 2003).

Using spatial environmental data, species distribution models (bioclimatic envelope models) can be used to infer habitat suitability and species' range limits (Guisan and Zimmermann, 2000; Kearney and Porter, 2009). A review of the different techniques used in species distribution modelling is provided by Guisan and Zimmermann (2000), and a comprehensive comparison of the accuracy of different methods was undertaken by Elith *et al*. (2006). Species distribution models have been used in wide ranging studies including, predicting future species distributions under climatic change (Huntley *et al*., 1995; Sykes *et al*., 1996; Thuiller *et al*., 2005; Penman *et al*., 2010; Yates *et al*., 2010a), identifying species at risk from extinction as a consequence of climatic change (Thomas *et al*., 2004; Ohlemüller *et al*., 2006; Bässler *et al*., 2010), and informing conservation strategies and policies (Hannah *et al*., 2002; Pyke *et al*., 2005).

Bioclimatic envelopes are established, using correlations between a species distribution and climatic conditions (Guisan and Zimmermann, 2000; Pearson and Dawson, 2003; Thuiller *et al*., 2005; Foody, 2008). A bioclimatic envelope can be constructed in a number of ways. If presence-absence data is available, and therefore the current distribution of a species is known, current climatic variables for the sites where the species is present or absent can be identified (Guisan and Zimmerman, 2000; Pearson and Dawson, 2003; Thuiller *et al*., 2005; Foody., 2008; Bässler *et al*., 2010; Montoya *et al*., 2009; Penman *et al*., 2010). From this information, a bioclimatic envelope can be inferred, which represents the present day realised niche of the species.

A second approach to bioclimatic envelope modelling is to use physiological data to infer the potential distribution, (or fundamental niche), of a species (Pearson and Dawson, 2003; Kearney and Porter, 2009). This approach is particularly useful if contemporary presence-absence distribution data is unavailable for the geographical area of interest. A physiologically based species distribution model links known functional traits of a species with bioclimatic variables, and identifies if a specific location is climatically suited to a particular species (Kearney and Porter, 2009).

There are well documented limitations to the capabilities of bioclimatic envelope models, based on both physiological, and correlative data (Pearson and Dawson, 2003; Guisan and Thuiller, 2005; Elith *et al*., 2006; Kearney and Porter, 2009), but there is agreement that their use at large spatial scales can provide useful, and accurate information, on the relationship between climate conditions and species distributions (Pearson and Dawson, 2003).

This chapter determines the climatically suitable regions for *C. arabica* in eight East African countries, using a bioclimatic envelope approach (Guisan and Zimmermann, 2000). Optimal and tolerable climatic thresholds for arabica coffee are first identified, before calculating the number of such locations through time, and mapping their distribution over the past 40 years. Climatic trends in mean annual temperature and total annual precipitation since 1961 are shown.

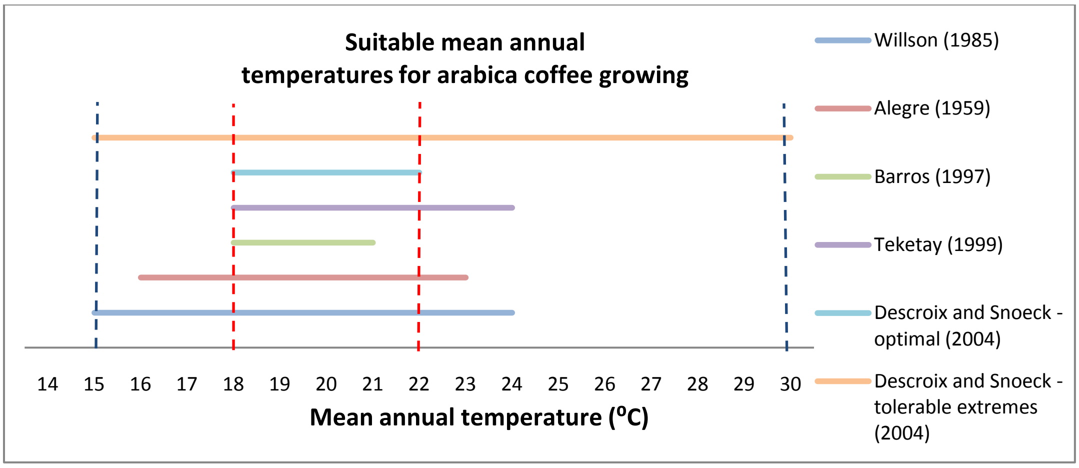
3.2 Methods

3.2.1 Identifying the climatic requirements for the growth and development of Coffea arabica

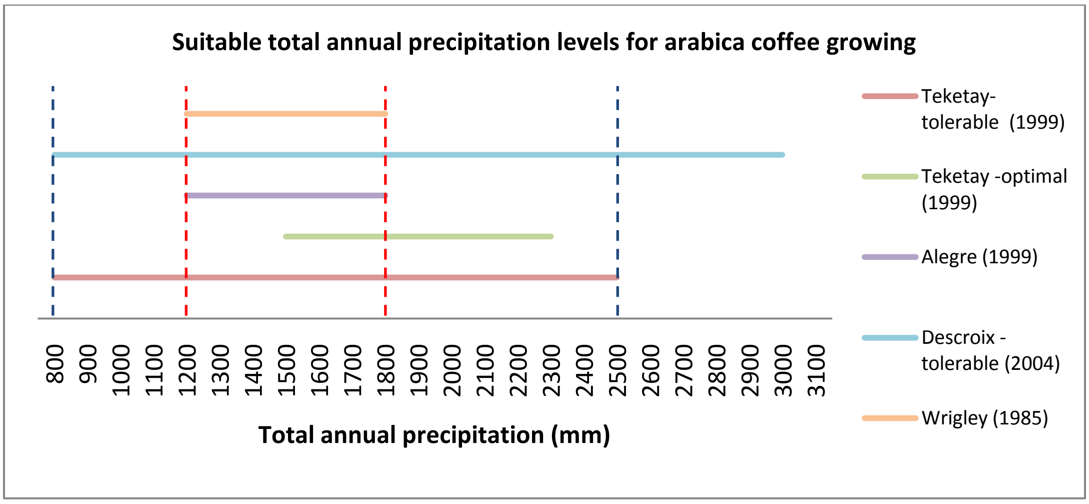
East Africa is a remote region, and accurate and detailed crop distribution data, including the locations of current arabica coffee growing regions is not widely available (You at al., 2009; Thornton *et al*., 2010). In many studies, correlative models based on current distribution-climate relationships have been used to determine a regions' climatic suitability for a specific species (Guisan and Zimmermann, 2000; Guisan and Thuiller; 2005, Yates *et al*., 2010a). However, due to the lack of detailed arabica coffee distribution data available for East Africa, a correlative model using presence-absence data was not suitable for determining the areas of East Africa currently climatically suitability for coffee.

In the absence of reliable distribution data for much of the climate space suitable for coffee, an alternative approach, using known climatic thresholds for *C. arabica* obtained from previous studies, was used to map the climatic suitability of coffee in East Africa. This approach follows the BIOCLIM method (Kearney and Porter, 2009; Santika and Hutchinson, 2009), which defines the suitable climate envelope of a species, as the climatic conditions within the minimum and maximum values of a number of climate variables. No actual distribution records were available so the minimum and maximum values for arabica coffee were derived from published sources rather than actual distribution records. Two main climatic variables were found to limit the success of arabica coffee growth: mean annual temperature and total annual precipitation (Alegre, 1959 cited from DaMatta, 2004; Willson, 1985; Wrigley, 1985; Barros, 1997; Teketay, 1999; Descroix and Snoeck, 2004).

The minimum and maximum values of mean annual temperature and total annual precipitation were used to define optimal and tolerable thresholds (Fig. 3.1). Optimal temperatures were defined as those between 18°C and 22°C, and total precipitation between 1200mm and 1800mm per year, as this is the narrowest range of climatic conditions given by a number of published studies (Fig. 3.1). Tolerable conditions were identified as areas with mean annual temperatures between 15°C and 30°C, and total precipitation between 800mm and 2500mm a year, as these were the widest thresholds given in a number of studies (Fig. 3.1).



a)

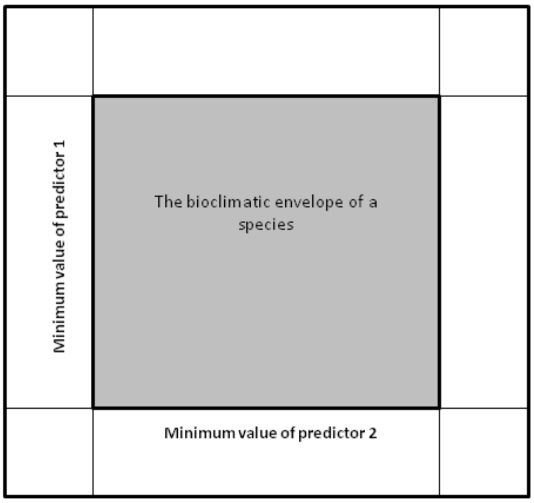


b)

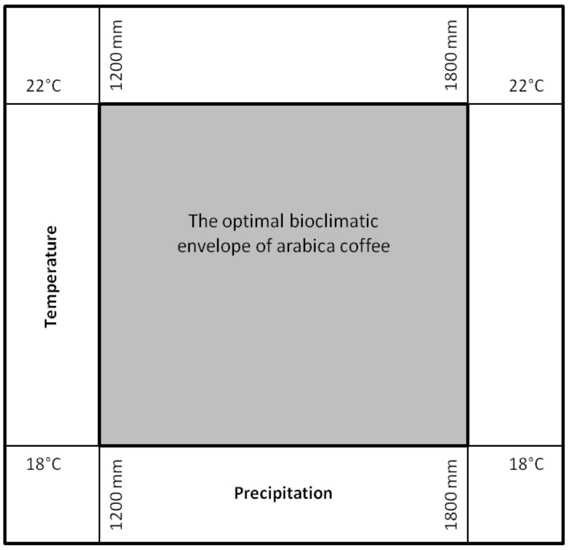
Figure 3.1: Climatic requirements for *Coffea arabica* for a) mean annual temperature and b) total annual precipitation. Red dotted lines represent the boundaries of conditions considered as optimal, and blue dotted lines represent the boundaries considered as tolerable.

3.2.2 The bioclimatic envelope of arabica coffee

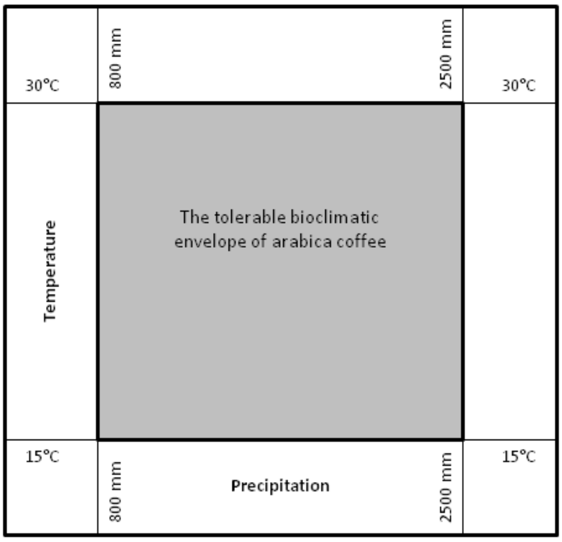
The optimal and tolerable thresholds identified in section 3.2.1 were used to delineate the tolerable and optimal bioclimatic envelope for *C. arabica* in eastern Africa, at a 0.5°×0.5° grid cell resolution. The resulting envelope is bounded by the upper and lower limits (Fig. 3.2a) for each environmental variable, and can be projected onto current and future climate scenario grids. Locations with climatic variables within the envelope are classed as climatically suitable locations, where as those located outside of the envelope are deemed unsuitable for the species studied. Figure 3.2b shows the tolerable bioclimatic envelope for *C. arabica*, with total annual precipitation and mean annual temperature as predictor variables. This approach can further be used to predict the optimal locations for growth of arabica coffee (Fig. 3.2c).



a)



b)



c)

Figure 3.2 a) A two-dimensional bioclimatic envelope for a species (Guisan & Zimmerman, 2000) b) The optimal bioclimatic envelope for *C. arabica* growth c) The tolerable bioclimatic envelope for *C. arabic*a growth.

The global CRU_TS_2.10 dataset, (Mitchell and Jones, 2005) was used to identify locations that fall within the optimal and tolerable climatic thresholds for both climate variables (Fig. 3.2). The numbers of optimal and tolerable locations, (a location is classified as one 0.5°×0.5° grid cell), were plotted through time (annually 1961 - 2002), and trends in climatic suitability identified using linear regression. The geographical distributions of optimal and tolerable locations were identified using decadal average climate values, and then mapped using ArcGIS.

The present day climate space of all locations within East Africa were shown using mean annual temperatures and total annual precipitation based on the average 1990-99 values. The boundaries of optimal and tolerable locations were identified, to show the distribution of present day locations within these boundary thresholds. Using data available from FAO (2009), the actual land area of coffee harvested per country each year from 1961 - 2002 was plotted, so trends in this data could be compared with the number of suitable arabica coffee growing locations.

Aside from mean annual temperatures, other variables may affect coffee growth. For example, species distribution studies have used factors such as, mean temperature of the warmest month MTWA, mean temperature of the coldest month MTCO, annual and seasonal maximum mean temperatures, annual and seasonal minimum mean temperatures, and actual to potential evapotranspiration APET, in bioclimatic envelope models (Beaumont *et al*., 2007; Montoya *et al.,* 2009; Yates *et al*., 2010a). These thresholds for arabica coffee were not identified in the literature consulted. These bioclimatic variables were identified for known coffee growing locations in Ethiopia, and compared with areas where coffee is not currently produced.

3.2.3 Model evaluation

Arabica coffee distribution data was only available for Ethiopia, and it is assumed that this map represents the present day distribution of coffee (iKhofi, 2009). These maps were digitised using a grid at a 0.5°×0.5° resolution, to identify the current spatial distribution of arabica coffee. Regions of coffee production were identified into two systems, garden coffee and wild forest coffee (Petit, 2007). Using the bioclimatic envelope, regions that are at present climatically suitable for coffee in Ethiopia were identified. Three types of environment were identified: tolerable locations, optimum locations, and thirdly, regions unsuitable for growth, classified as ‘no coffee’.

To assess the performance of our bioclimatic model, the predicted areas of climatic suitability for arabica coffee in Ethiopia, were compared with those of actual coffee growing locations. Confusion matrices were constructed, and four possible outcomes for each location were calculated:

a) True positives - the model predicted coffee in this location, and coffee is at present found in this location.

b) False positives - the model predicted coffee in this region, but present day distribution data suggests that coffee is not grown in this location.

c) False negatives - the model implies this location is unsuitable for coffee growth, but coffee is at present produced in this location.

d) True negatives - the model implies that region is unsuitable for coffee, and coffee is not currently present in this location.

These results were summarised by calculating sensitivity and specificity statistics (Liu *et al*., 2005; Foody, 2008). Sensitivity was calculated as a/(a+c), with high values indicating that the model has a high capacity to predict actual growing locations; specificity was calculated as d/(b+d), with high values indicating that the model has a high capacity to predict locations where coffee is currently not grown.

Using the CRU_TS_2.10 dataset, mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA), and ratio of actual evapotranspiration to potential evapotranspiration (APET), bioclimatic variables were derived. Using these variables, in addition to mean annual temperatures and annual total precipitation, the bioclimatic envelope of forest and garden coffee locations in Ethiopia, and non-coffee locations, were compared in a 2D diagram of the Ethiopian climate space.

3.3 Results

3.3.1 The climatic trends and actual area of coffee harvested since 1961

In this first section of results, the trends in temperature and precipitation over the past 40 years for each of the eight countries studied are examined. Full details of these trends are presented in Appendix One. Over the past 40 years, there has been a gradual rise in mean annual temperature, and a decline in total annual precipitation in all eight East African countries studied (Table 3.1). The range in mean annual temperatures across the eight countries studied is 6.7°C. Rwanda is the coolest country, with a mean annual temperature of 18.1°C, but temperatures here have risen the most rapidly, with an average increase of 0.039°C per year (Table 3.1). The warmest country studied is Kenya, with mean annual temperatures of 24.8°C. The highest mean annual temperature recorded is 25.5°C in Kenya in 2002 (Appendix One). In all of the countries studied, temperatures have risen above the 1961 - 2002 average (21.7°C) since the mid-1980s, with all countries showing record high mean annual temperatures between the years 2000 and 2002 (Appendix One). This supports other study findings that the East African region has been warming over the past 40 years (Boko *et al*., 2007).

Table 3.1: Trends in the average temperature, total precipitation, coffee area harvested, and number of optimal and tolerable coffee growing locations in eight East African countries between 1961 and 2002.

Country	Mean temperature change per year (ºC)	Significance (p values)	Mean precipitation change per year (mm)	Significance (p values)	Average change in the number of optimal locations per year	Average change in the number of tolerable locations per year
Burundi	0.035	0.000*	-4.245	0.013*	-0.07	0.00
Ethiopia	0.023	0.000*	-2.595	0.024*	-0.36	-0.73
Kenya	0.015	0.000*	-3.241	0.051	-0.03	-0.30
Malawi	0.017	0.000*	-3.863	0.055	-0.09	-0.06
Rwanda	0.039	0.000*	-5.246	0.001*	0.00	-0.04
Tanzania	0.019	0.000*	-2.915	0.077	-0.79	-0.35
Uganda	0.033	0.000*	-6.123	0.001*	-0.40	-0.27
Zambia	0.029	0.000*	-3.453	0.035*	-1.33	-0.56
All countries (including Uganda)	0.026	0.000*	-3.960	0.000*	-3.08	-2.31
All countries (excluding Uganda)	0.025	0.000*	-3.651	0.001*	-2.68	-2.04

*Values are significant at the 0.05 level (2-tailed)

Total annual precipitation in each country varies, from a maximum of 1202mm per year in Burundi to just 675mm per year in Kenya (based on mean 1961-2002 annual values) (Appendix One). Across all countries studied, there is a declining trend in precipitation between 1961 and 2002, and these trends are significant in five of the countries studied (Appendix 1 and Table 3.1). This supports the findings of previous climate change studies, which highlight the declining trend in precipitation across East Africa (Slingo *et al*., 2005; Boko *et al*., 2007; Funk *et al*., 2008). Arabica coffee is grown in all of the eight countries included in the study, despite the climatic ranges.

From 1961 to 2002, the region has become warmer and drier (Appendix One). Using averages of mean annual temperatures, and total annual precipitation between 1990-99, it can be seen that the majority of locations lie outside of the optimal climatic range for arabica coffee (Fig. 3.3). Currently, 60% of the locations in the eight East African countries studied have climatic conditions that are classed as tolerable for arabica coffee growing (Fig. 3.3). Eleven locations across the region are too cool, and the remaining areas that are unsuitable for coffee are too dry. If the current climate trends continue (resulting in hotter, drier weather), more land cells will shift towards the edge of the bioclimatic envelope and many may fall outside of the tolerable conditions (Fig. 3.3). The optimal bioclimatic envelope, based on the 1990-99 climatic variable averages is already on the edge of the current temperature-precipitation climate space (Fig. 3.3). This indicates that coffee is on the edge of its bioclimatic envelope in the region, and that future climatic changes could have implications for arabica coffee distribution.

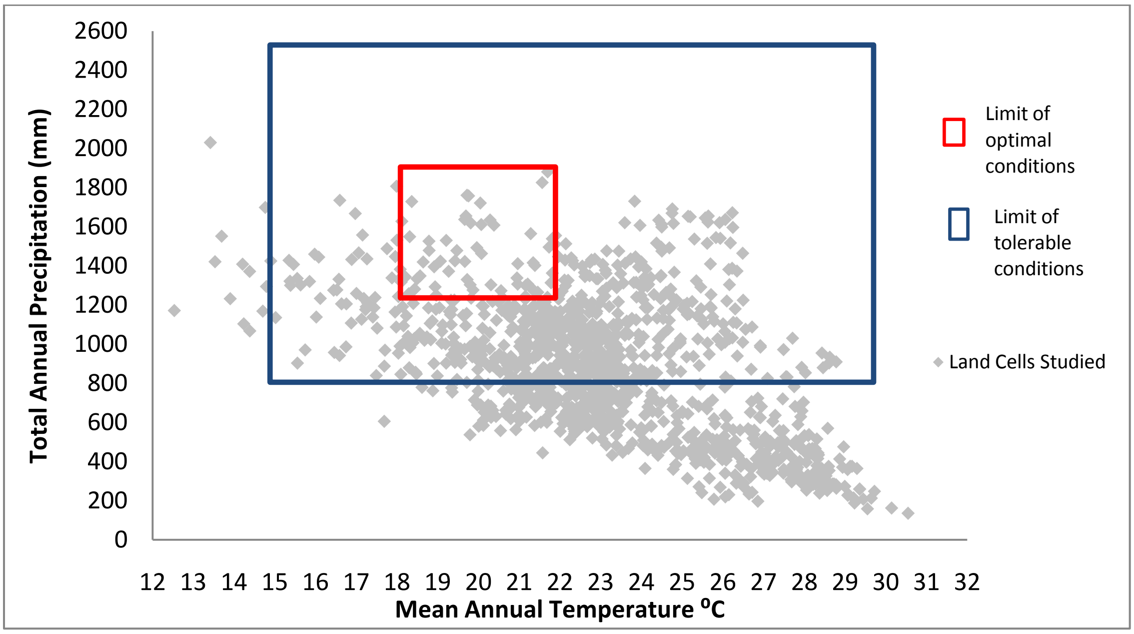
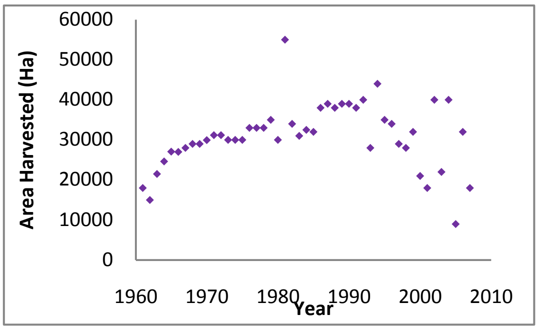
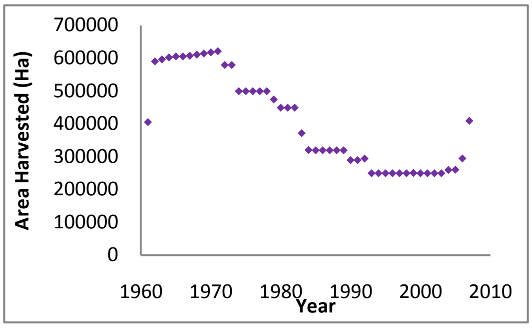


Figure 3.3: Optimal and tolerable conditions for *C. arabica* in a 2-dimensional climate space (mean annual temperature, total annual precipitation), based upon the average 1990-1999 climatic conditions of all land grid cells of the eight East African countries investigated.

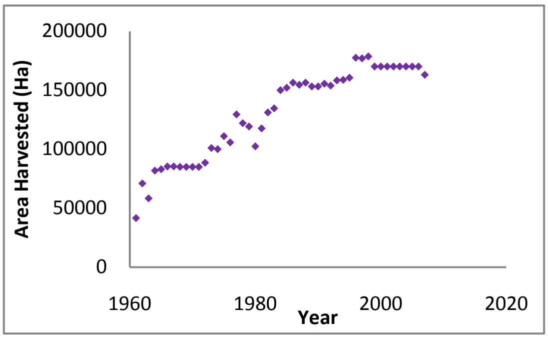
Although no detailed information regarding the number of and locations of arabica coffee growing locations were available, Fig. 3.4 shows that there is considerable variation between countries as to the coffee area harvested each year. The coffee area harvested in Ethiopia and Uganda has declined since 1961, but in Burundi, Kenya, Malawi, Rwanda, Tanzania, and Zambia the coffee area harvested has increased (Fig. 3.4).

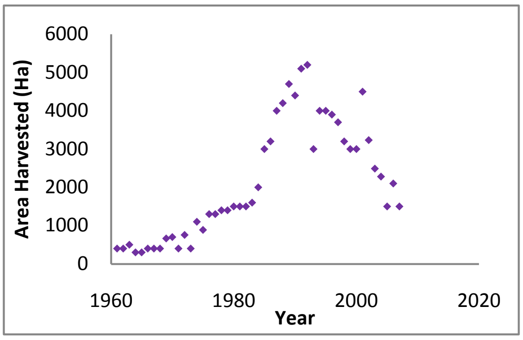




a) Burundi

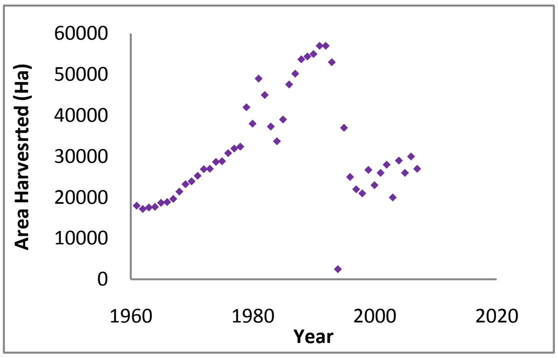
b) Ethiopia

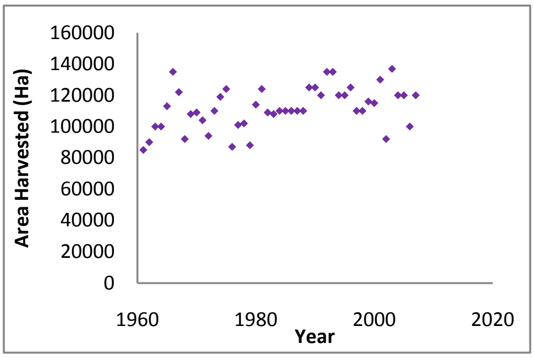




c) Kenya

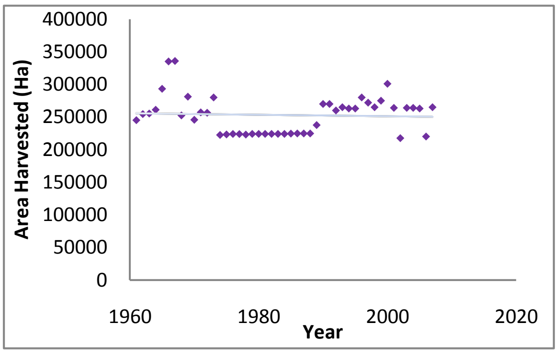
d) Malawi

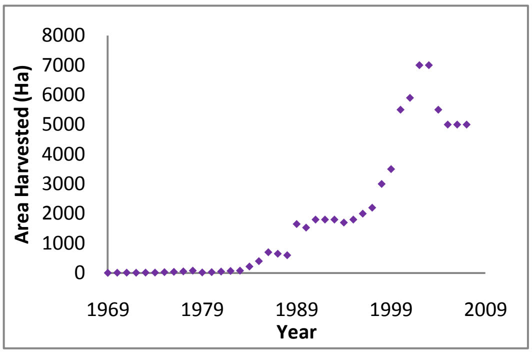




e) Rwanda

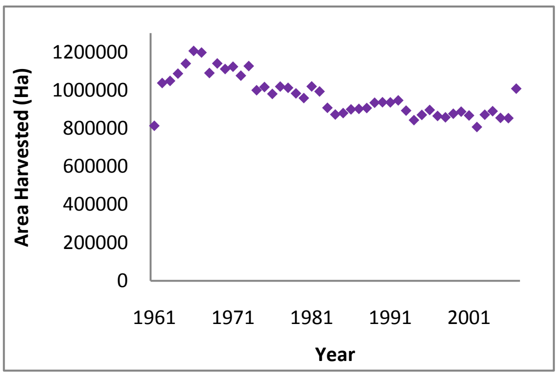
f) Tanzania

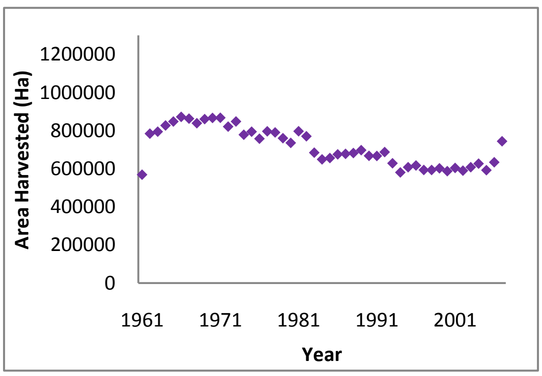




g) Uganda

h) Zambia





i) All countries (including Uganda)

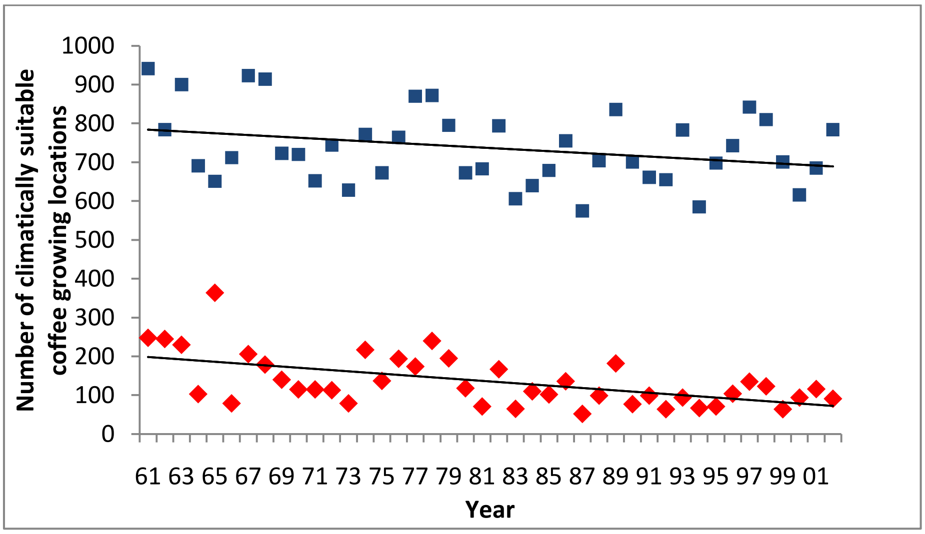
j) All countries (excluding Uganda)

Fig 3.4: Actual area of land harvested for arabica coffee within each country over time (FAO, 2009)

3.3.2 The number of climatically suitable arabica coffee growing locations

In the eight East African countries investigated, the mean number of tolerable locations across the time period studied is approximately 750 locations, and around 150 locations have optimal conditions (Fig. 3.5). Uganda primarily grows coffee of the robusta variety, and only 4% of coffee grown in the country is of the arabica variety (EAFCA, 2009). For this reason, Uganda is excluded from some of the analyses in this study. When Uganda is excluded from the above analysis there are approximately 680 tolerable locations and 140 optimal coffee growing sites (Fig. 3.5). There is a clear declining trend in both the number of optimal and tolerable locations between 1961 and 2002. On average, 3.08 optimal locations were lost annually, and tolerable sites declined on average by 2.30 per year. When Uganda is excluded from the analysis 2.68 locations are lost each year and optimal sites decline on average by 2.04 a year (Fig. 3.5 and Table 3.1).

a) All countries



b) All countries, excluding Uganda

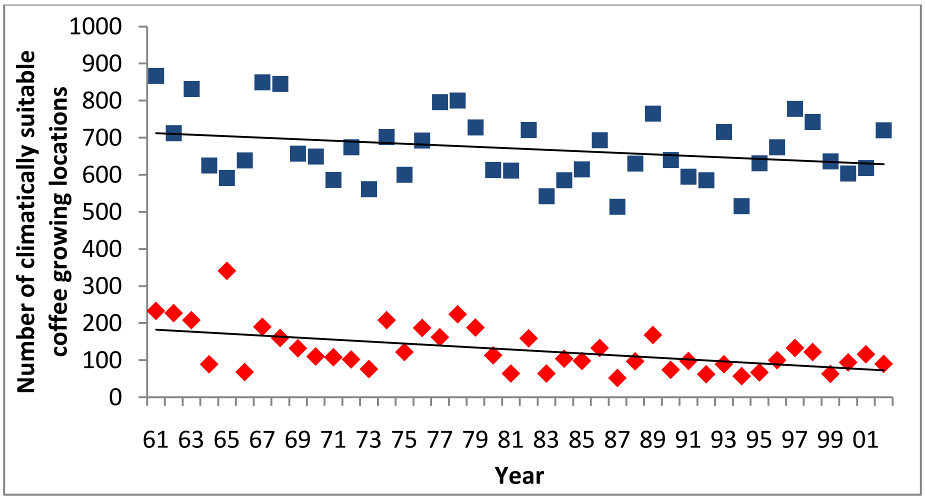
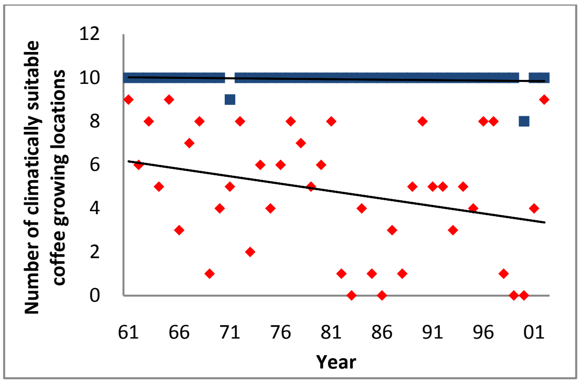


Figure 3.5: Total number of optimal (blue) and tolerable (red) coffee growing locations in eight East African countries.

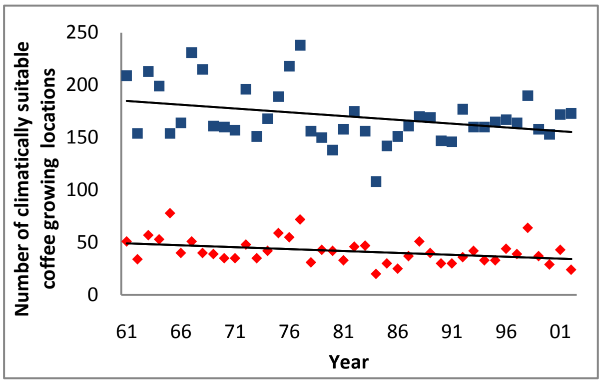
From 1961 to 2002, the number of optimal coffee growing locations in the eight countries studied varied between 52 and 364 locations (Fig. 3.5). The greatest inter-annual variation was observed in the 1960s and 1970s, with a decline in variation, and total number of optimal locations since the early 1980s. Since 1990, the number of optimal coffee growing locations has varied between 64 and 135 sites (Fig. 3.5a).

Between 1961 and 2002, the total number of tolerable coffee growing locations has varied from 575 to 941 (Fig. 3.5a). The highest numbers of tolerable locations were recorded during the 1960s, and inter-annual variation was greatest in the late 1960s and early 1970s. Since 1980, the number of tolerable locations has ranged from 575 to 836 (Fig. 3.5). The severity of the decline in optimal locations for coffee varies between countries, with the largest decline observed in Zambia (average loss of -1.33 locations per year). On average, the number of optimal locations in Rwanda does not decline during the period studied (Table 3.1).

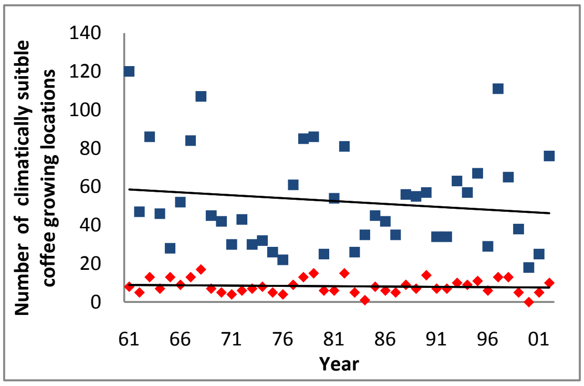
Despite the decline in annual precipitation, rise in mean annual temperature, and predicted decrease in the number of optimal and tolerable locations across the region, all countries apart from Ethiopia and Uganda, show an increase in the actual coffee area harvested (Fig. 3.4). This suggests that there are factors (both environmental and socio-economic), other than mean annual temperature and total precipitation that affect coffee production. However, here and throughout this study it needs to be noted that coffee area harvested and the number of suitable locations are not directly comparable, because even if locations are identified as suitable, all the land area within these grid cell locations will not be planted with coffee.



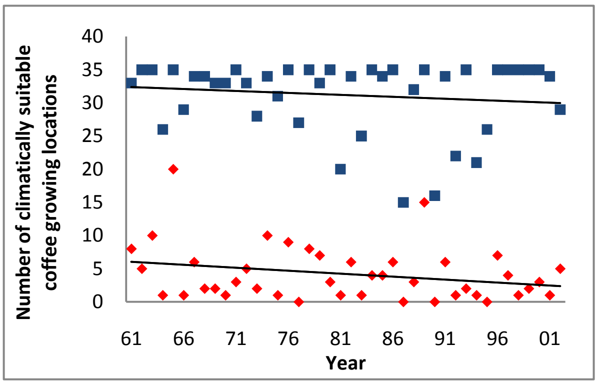
a) Burundi (n= 10)



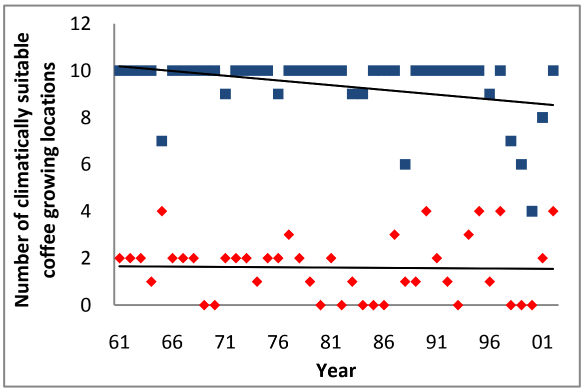
b) Ethiopia (n= 369)



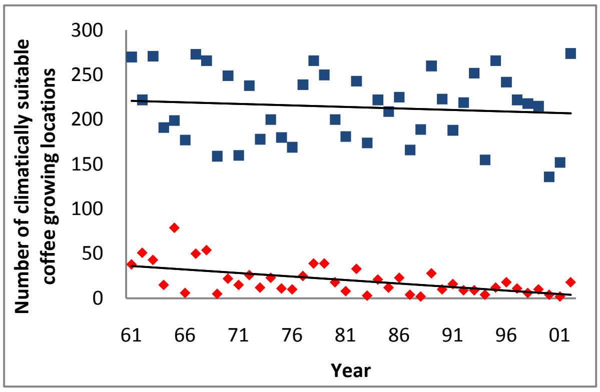
c) Kenya (n= 189)



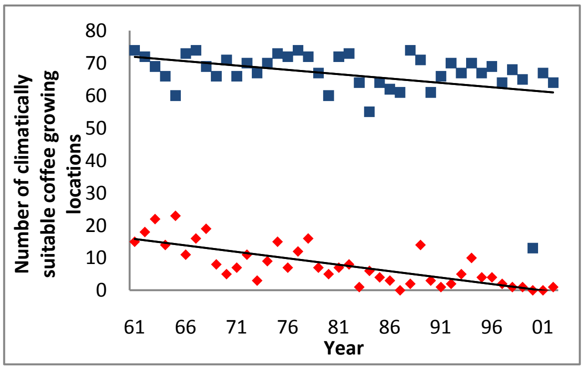
d) Malawi (n= 35)



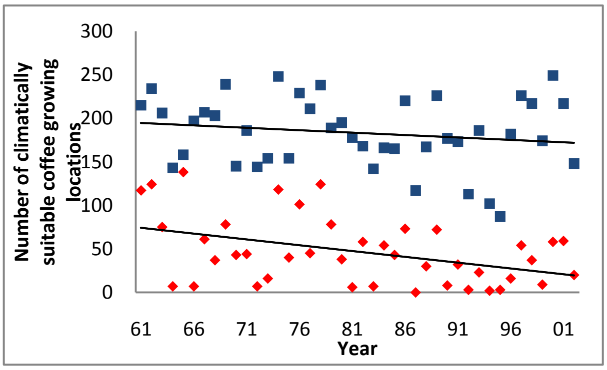
e) Rwanda (n= 10)



f) Tanzania (n= 293)



g) Uganda (n= 74)



h) Zambia (n= 249)

Figure 3.6: The number of optimal (blue) and tolerable (red) coffee growing locations in eight East African countries (n = total number of land grid cells in country)

3.3.3 The geographical distribution of coffee locations in eight East African countries

Using decadal climate averages of mean annual temperature and total annual precipitation, the distribution of locations with tolerable and optimal climatic conditions for arabica coffee were identified (Fig. 3.7).

Of the four decades studied, the numbers of both optimal and tolerable coffee growing sites were highest during the 1960s. Tolerable sites have historically been distributed throughout the East African region, in particularly in Burundi, Uganda, Rwanda, Zambia, Malawi, western Ethiopia, and Northwest Tanzania. Optimal coffee locations are historically found in western Ethiopia, North Zambia, and Burundi, with sparse and varying distributions in Kenya, Malawi, Rwanda and Tanzania.

Between 1961 and 2002, the total number of tolerable coffee growing sites in East Africa has declined by 9.8%. The distribution of tolerable coffee growing sites has declined most noticeably in Zambia, and southern Ethiopia (Fig. 3.7). The areas of central Kenya, western Tanzania, and Zambia have also been affected (Fig. 3.7). Overall there was a decline of 45% in the total number of optimal sites in the East African region studied between the 1960s and 2000-02. Ethiopia experienced the largest actual decline in coffee area harvested (Fig. 3.4), and the numbers of optimal coffee growing locations have decreased the most in Zambia, western Tanzania, Uganda, and Southwest Ethiopia (Fig. 3.6 & 3.7).

From 1961 to 2002, no new areas emerged as tolerable or optimal growing locations. Nevertheless, although the number of suitable sites did not increase, the increasing areas of coffee harvested suggest that new land may have been planted or converted to coffee within suitable growing locations (Fig. 3.4). The largest rises per country in terms of coffee area harvested, are Kenya, Rwanda and Tanzania.

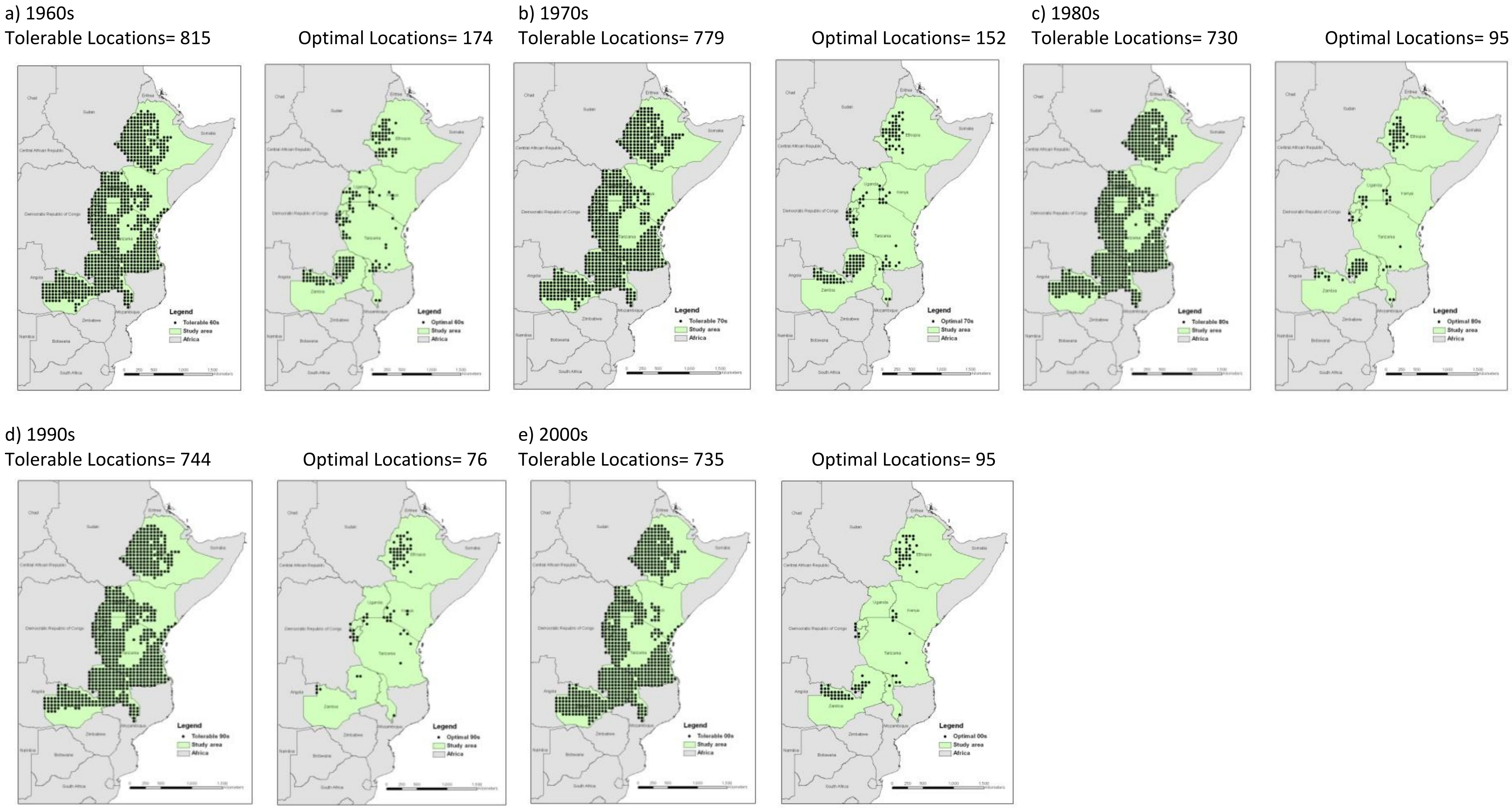
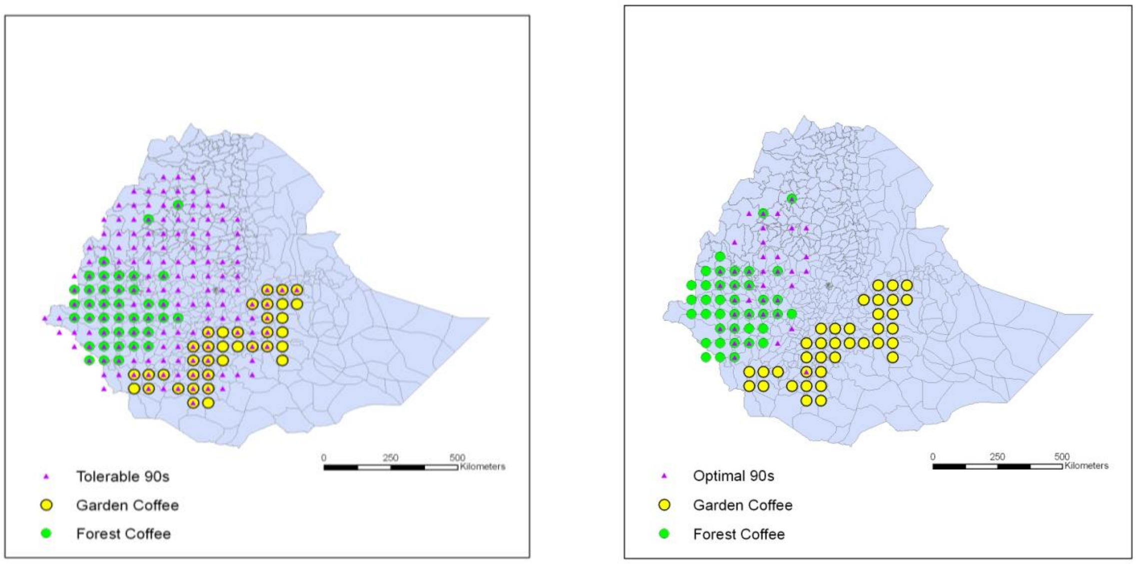


Figure 3.7: The geographical distribution of optimal and tolerable coffee growing locations, based on decadal mean annual temperatures and total annual precipitation between 1961 and 2002.

3.3.4 Predicted and actual C. arabica growing locations in Ethiopia

After digitising the coffee distribution maps for Ethiopia, the present day coffee growing locations in the country were identified, using the bioclimatic envelope. The results from the bioclimatic model of predicted coffee growing locations, was compared with actual coffee growing sites. A visual comparison between predicted and actual coffee distribution is shown in Fig. 3.8.



b)

Figure 3.8: Predicted and actual coffee growing locations in Ethiopia using (a) tolerable and (b) optimal climatic thresholds, based on 1990-99 climate averages.

There is a good agreement between the number of tolerable growing sites and actual coffee growing locations, and this can be quantified further by analysing the number of true positives, false positives, false negatives and true negatives (Section 3.2.3).

This information can be presented in a confusion matrix table (Table 3.2), and used to calculate the sensitivity (ability to predict actual coffee growing sites) and specificity (ability to predict areas that coffee does not grow) of the bioclimatic model.

Table 3.2 Indicators of the performance of the bioclimatic model. a) The identification of true positive, false positive, true negative and false negative indicators. b) The performance of the bioclimatic model when tolerable climatic thresholds are used. c) The performance of the bioclimatic model when optimal climatic thresholds are used.

a)

		Predicted Coffee	**Predicted** No Coffee
Actual	Coffee	True Positive (correct prediction)	False Negative
Actual	No Coffee	False Positive	True Negative (correct prediction)

Sensitivity = $\frac{\text{True Positives}}{\text{(True positives + False negatives)}}$

Specificity = $\frac{\text{True Negative}}{\text{(True negative + False positive)}}$

Sum of sensitivity and specificity = Sensitivity + Specificity

b) Tolerable conditions

I) Forest coffee

		Predicted coffee	**Predicted** no coffee
Actual	coffee	39	0
	no coffee	126	204

sensitivity = 1.00
specificity = 0.62
Sum of sensitivity and specificity = 1.62

II) Garden coffee

		Predicted coffee	**Predicted** no coffee
Actual	coffee	25	12
	no coffee	140	192

sensitivity = 0.68
specificity = 0.58
Sum of sensitivity and specificity = 1.26

c) Optimal conditions

I) Forest coffee

		Predicted coffee	**Predicted** no coffee
Actual	coffee	21	18
	no coffee	19	311

sensitivity = 0.54
specificity =0.94
Sum of sensitivity and specificity = 1.48

II) Garden coffee

		Predicted coffee	**Predicted** no coffee
Actual	coffee	1	36
	no coffee	39	293

sensitivity = 0.03
specificity = 0.88
Sum of sensitivity and specificity = 0.91

Using the wider (tolerable) climate conditions, the bioclimatic model correctly identifies all forest coffee regions, and 68% of garden coffee regions as climatically suitable (Fig. 3.8a). Using the narrower (optimal) climate conditions, 54% of the actual forest coffee growing locations, and 3% of garden coffee locations are correctly identified. Our model is accurate at predicting tolerable areas of coffee growing locations, in particular forest grown coffee. The model shows high levels of sensitivity. Using optimal climatic conditions, the model shows high specificity, indentifying areas that coffee is not grown in but sensitivity is poor, especially when the model is identifying areas of garden coffee (Table 3.2).

A 2D climate-envelope space was then plotted, showing the climatic conditions of known forest coffee, garden coffee and sites unsuitable for coffee (termed no coffee) locations in Ethiopia (Fig. 3.9). Garden coffee locations are generally located closer to the edge of the tolerable coffee growing envelope than forest coffee locations (Fig. 3.9). Several garden coffee locations are outside the tolerable coffee growing conditions identified in this study. Forest coffee locations are all found within the tolerable bioclimatic envelope and 54% of forest coffee is found within the optimal bioclimatic envelope.

Non-coffee locations are generally limited by low levels of precipitation rather than temperature. If the current climate trends continue, and Ethiopia becomes warmer and drier, the number of garden coffee areas outside of the tolerable coffee growing conditions identified will increase. This is in line with the trends in the overall climate space of the East African region shown in Fig. 3.3.

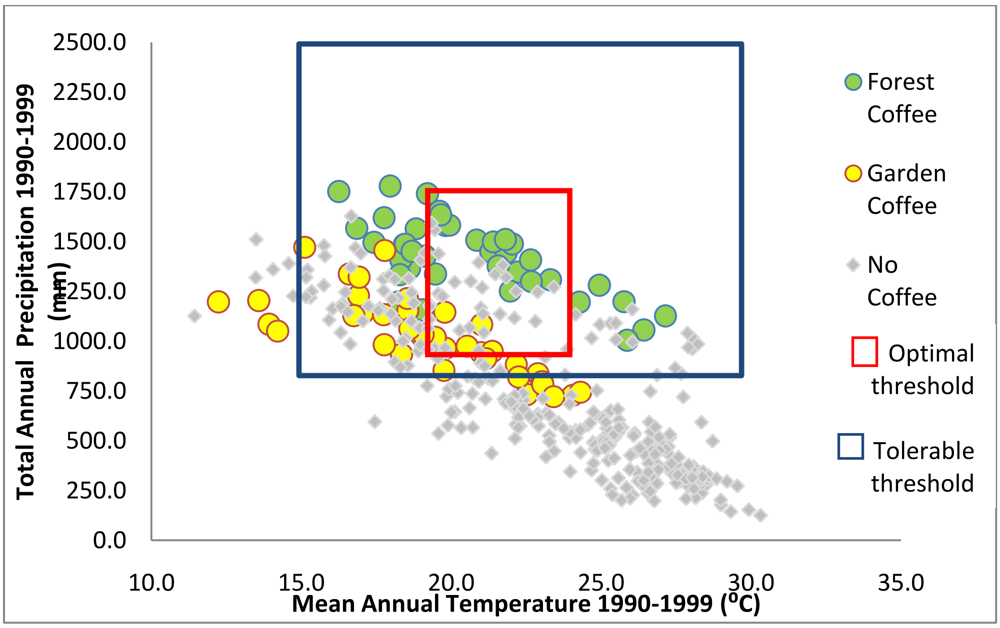
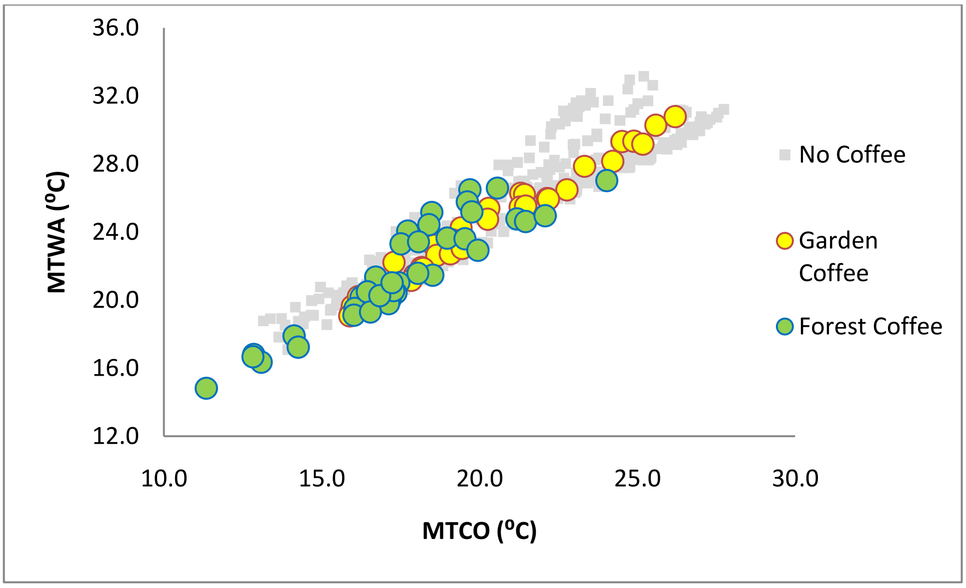
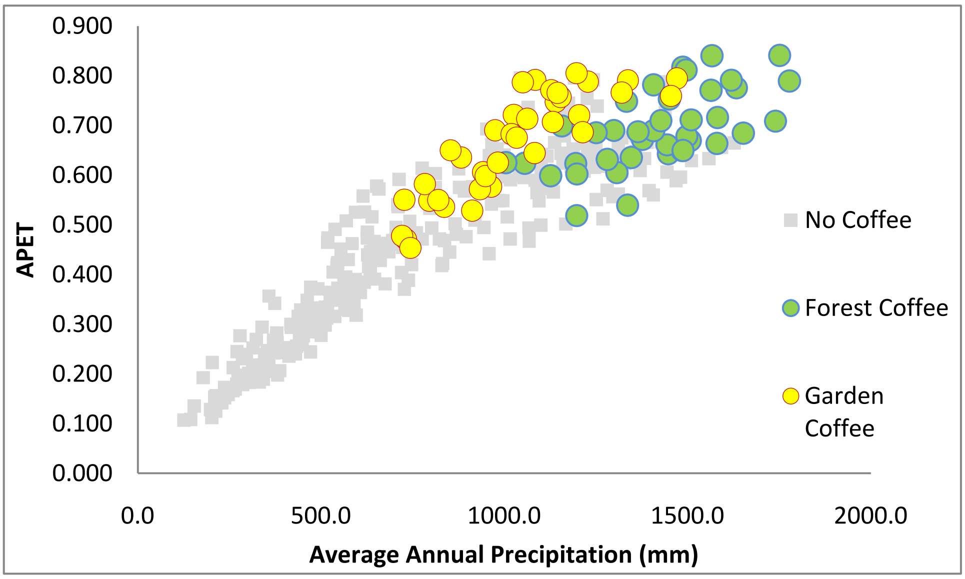


Figure 3.9: The bioclimatic envelope of forest and garden coffee growing locations in Ethiopia

Means were calculated for the bioclimatic variables, MTCO, MTWA, and APET, based upon 1990-99 values for the known locations of coffee growing locations in Ethiopia. Plotting these bioclimatic variables in a 2D climate envelope reveals that MTCO and MTWA are not useful variables in identify coffee growing locations, because there is a large overlap between non-coffee, forest coffee and garden coffee growing locations. APET is a more useful bioclimatic variable, and all coffee growing locations have an APET value greater that 0.40 (Fig. 3.10).



a)



b)

Figure 3.10: a) Mean temperature of the coldest month (MTCO) and mean temperature of the warmest month (MTWA) for coffee and non-coffee sites in Ethiopia. b) The average annual precipitation and actual/potential evapotranspiration (APET) of coffee and non-coffee sites in Ethiopia.

Coffee System	Mean Annual Temperature (°C)		Total annual precipitation (mm)		MTCO (ºC)		MTWA (ºC)		APET	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Forest Coffee	12.2	24.0	995.7	1778.2	11.3	23.9	14.8	27.2	0.519	0.841
Garden Coffee	16.3	27.1	721.2	1471.0	15.9	26.4	19.3	31.2	0.471	0.788

Table 3.3: The bioclimatic envelope of actual Ethiopian coffee growing locations

The actual bioclimatic envelope of Ethiopian coffee fits the tolerable conditions identified from the literature (15ºC - 30ºC and 800mm - 2500mm of precipitation). The extent of the tolerable precipitation identified through the literature (2500mm), (Teketay, 1999; Descroix and Snoeck, 2004) is far in excess of the actual maximum annual precipitation (1778.2 mm) that coffee is found in.

3.4 Discussion

3.4.1 Climatic variation and coffee distribution

A number of previous studies indicate that coffee is a climatically sensitive crop, and optimal conditions for production are areas with mean annual temperatures between 18ºC and 22ºC, and total annual precipitation between 1200mm and 1800mm (Alègre, 1959; Teketay, 1999; Descroix and Snoeck, 2004; Tucker *et al*; 2010). In this study, tolerable conditions for arabica coffee growing were defined as locations with mean annual temperatures between 15°C and 30°C, and total annual precipitation between 800mm and 2500mm.

Climatic changes in Africa over the past 40 years are well documented. The region has become hotter and generally drier, with a rise in mean annual temperatures across all countries (Boko *et al*, 2007; Funk *et al*., 2008). Under the present day climatic conditions, arabica coffee is at the limit of its bioclimatic envelope in large parts of Ethiopia, especially coffee grown in garden coffee systems (Fig. 3.3). More than 50% of locations in Ethiopia currently have mean annual temperatures higher than the optimal threshold (22°C). Similarly, in a study of arabica coffee in Veracruz, Mexico, Gay *et al*., (2006), found that coffee at present is growing in regions where mean annual temperatures are above the optimal defined for the species. This suggests that arabica coffee growth in these areas is particularly vulnerable to climatic change: warming temperatures may push coffee further beyond its bioclimatic envelope and, may lead to decreased yields and loss of fruit quality. Coffee production is negatively affected by high temperatures above 30°C (Wilson, 1985; DaMatta, 2004; Descroix and Snoeck, 2004).

Based on the present day (1990-99 climatic averages), the number of tolerable locations is limited by precipitation, with many regions receiving less than 800mm of precipitation each year (Fig. 3.3). In the future, further reductions in rainfall may reduce the areas suitable for arabica coffee, and yields may decline. There is already some evidence that coffee producers are implementing adaptation strategies in response to this: for example, in some parts of the world, such as Mexico, secondary species have been planted to provide shade and reduce evapotranspiration (Lin, 2007). Growers in East Africa may have to explore such methods of mitigation, if precipitation continues to decline, or becomes increasingly variable. Delayed, or low levels of precipitation in East African regions, severely affects crops harvests and can result in yields far lower than expected, or lead to complete crop failure. Evidence for this was seen in 2008, when the late arrival and below average cumulative totals of rainfall, led to crop failure, and caused wide-spread food shortages across Ethiopia, western Kenya, Tanzania and Uganda (FAO, 2008).

The emerging trends over the past 40 years, of higher mean annual temperatures and in this study, declining precipitation, has coincided with a decline in the number of optimal and tolerable locations potentially suitable for arabica coffee (Fig. 3.5). Of the eight East African countries studied, Zambia shows the largest decline in the number of optimal locations (an average loss of 1.33 locations each year), and Ethiopia has the largest annual decline of tolerable locations (an average of 0.73 each year) (Table 3.1). After Zambia, Tanzania, on average, lost the largest number of optimal locations each year during the time period studied. Burundi and Rwanda have the smallest decline in the number of tolerable and optimal locations respectively, but they are amongst the smallest countries by land area studied (Table 3.1 and Fig. 3.6). Declining species distributions due to recent past climatic changes have become increasingly noted over the past decade: for example butterflies in the Sierra de Guadarrama mountain range in Spain have migrated upwards by 212m over the past 24 years, coinciding with a temperature increase of 1.3°C (Thomas *et al*., 2006). Three butterfly species studied in the United Kingdom have suffered from recent extinction in a number of locations. Climatic changes could have accounted for up 50% of these losses (Franco *et al*., 2006).

Temperatures increased the most in Burundi and Rwanda (on average 0.04°C per year), and precipitation declined the most in Uganda and Rwanda (average loss of 6.12mm and 5.25mm per year respectively). Rwanda had the third-highest average loss of both optimal and tolerable locations of the countries studied (Table 3.1).

The representation of the geographical distribution of optimal and tolerable locations over time (Fig. 3.7) illustrates the decline in the total number of tolerable and optimal locations. One region with a noticeable decline in the number of optimal and tolerable coffee growing locations is south-western Ethiopia, and this is supported by other studies. Garden coffee is particularly vulnerable because many areas where it is currently cultivated already fall outside of the tolerable bioclimatic envelope, but other studies have also shown a decline in the area of wild forest coffee in the region (Senbeta, 2007; Schmitt, 2009).

Wild forest coffee is an unmanaged growing system with lower than average yields (Labouisse *et al*., 2008). As land-pressure increases, and coffee regains economic value in the global market, there is increasing pressure to convert wild coffee forest into semi-forest coffee systems, with higher levels of management (Labouisse *et al*., 2008; Ambinakudige, 2009). This change in management intensity can result in deforestation, which can contribute to accelerated erosion, loss of soil water capacity and the alteration of the soil-nutrient cycle (Soini, 2005; Senbeta, 2006). Land-change is known to affect the local climate (Eakin *et al*., 2009) and the decline in wild forest coffee and deforestation in south-western Ethiopia may have contributed to the observed decline in the number of tolerable locations.

Over the past 40 years warmer mean annual temperatures and declining annual precipitation has coincided with a decline in the number of optimal and tolerable locations suitable for arabica coffee. Despite this decline in the number of climatically suitable sites across East Africa, the actual area of coffee harvested has increased in 75% of countries studied, suggesting that most countries have started to harvest greater areas of land within suitable coffee growing locations (Fig. 3.4). In Ethiopia and Uganda the area of coffee harvested has declined but both of these countries have experienced the same climatic trends as the rest of the region studied, (declining precipitation and warming temperatures), suggesting that the effects of climate change can have varying impacts across different landscapes, or perhaps the economic and technological situation within Ethiopia and Uganda, has not been favourable to increased harvesting (Tucker *et al*., 2010). If mean annual temperatures continue to increase, and precipitation decreases over the next century, it is expected that the number of optimal and tolerable locations will decline further (Fig. 3.3).

3.4.2 The bioclimatic envelope of forest and garden coffee in Ethiopia

All present day forest coffee sites are found within the tolerable climatic conditions outlined in this study, and 68% of garden coffee sites are found in locations identified as tolerable. The bioclimatic model that is more accurate in predicting forest coffee sites as these regions are un-managed. Coffee grown under the garden and plantation coffee systems is more highly managed, and may include irrigation or water management systems if annual precipitation is insufficient to provide adequate water availability (Petit, 2007; Labouisse *et al*., 2008). This model is unable to account for these management systems, and therefore the sensitivity and specificity is lower for garden coffee than forest coffee (Table 3.2).

The sensitivity of the model is good for tolerable climatic conditions, correctly predicting a large number of actual coffee growing sites for both forest and garden coffee. The sensitivity of the model when using optimal climatic conditions is poor, especially when predicting areas of garden coffee. The specificity of the model is high when optimal climatic conditions are used, and it correctly identifies a large number of locations that coffee in not grown in. (Table 3.3). The model over-predicts the number and location of coffee growing sites in some regions, for example the model suggests that there should be a large number of tolerable sites in Northwest Ethiopia, but coffee is not currently grown in these areas (Fig. 3.8). A number of reasons could account for this. In addition to adequate climatic conditions, (considered in this study as optimal or tolerable mean annual temperatures and precipitation) arabica coffee requires slightly acidic soil, and good source of mineral availability particularly potassium (Willson, 1985). Coffee is often cultivated in mountainous regions, and grows well at altitude, however, slopes must not be too steep, as this will affect water availability and rocky substrates will not have sufficient soil coverage for coffee plants to develop (Willson, 1985; Gay *et al*., 2006). Despite having suitable climatic conditions, the north-western region of Ethiopia is highly mountainous, and may not be topographically suited to arabica coffee.

Coffee is a labour intensive crop, and for the highest yields, coffee needs to be picked each year (Gay *et al*., 2006). For coffee grown in garden systems, plants must be pruned annually, and the process of picking coffee beans requires a large number of manual work hours, as the use of mechanized equipment in East Africa is low (Teketay, 1999). In some regions of Ethiopia, the bioclimatic envelope model may have identified regions that are climatically suitable, but do not have the available work force to manage and cultivate coffee, resulting in an over prediction of suitable coffee locations, reducing the sensitivity of the model. Although an important part of cultural heritage, particularly in Ethiopia, coffee is an important economic crop (Petit, 2007). Areas that are climatically suited to arabica coffee, but are not currently cultivating coffee, may be growing other export crops, and generating income from different cash crops that grow particularly well in the region. Coffee cultivation requires a significant initial investment to establish a small plantation, and some regions may not have had the capital available, or decided against this investment, despite suitable climatic conditions.

3.4.3 Non climatic factors affecting arabica coffee production in East Africa

The actual area of coffee harvested in most countries increased over the past 40 years, despite declining numbers of climatically suitable locations (Fig. 3.4 and Fig. 3.5). This suggests there are other factors that affect arabica coffee production, other than mean annual temperature and precipitation. These include, world coffee prices, change in land use, labour availability and the decision to harvest at a greater intensity in coffee growing regions (Soini, 2005; Ambinakudige *et al*., 2009; Eakin *et al*., 2009; Tucker *et al*., 2010).

In Burundi, Malawi and Rwanda, the area of coffee harvested shows a decline after 1990 (Fig. 3.4). This coincides with the collapse of the International Coffee Agreement in 1989, which caused coffee prices to crash and the world coffee market to become more volatile than previously experienced (Eakin *et al*., 2009; Ghosray, 2010; Tucker *et al*., 2010). Trading limits were no longer enforced and new countries entered the coffee market, resulting in a surplus of supplies. Many farmers could no longer afford to grow arabica coffee (Ghosray, 2010).

Other, non-climatic events can be determined from the data showing actual area harvested, including the 1994 Civil War in Rwanda (Verpoorten, 2009). Fig. 3.4 shows that in 1993 an area of 53,000 Ha of coffee was harvested in Rwanda. This dropped to just 2,500 Ha in 1994, and rose again to 37,000 Ha in 1995. This is an indication demonstrates that coffee production is strongly influenced by political and socio-economic activity, in addition to climatic variables (Gay *et al*., 2006).

The numbers of tolerable and optimal locations shown in this study were based on theoretical limitations defined through an extensive literature search. The actual bioclimatic envelope for coffee in Ethiopia (Table 3.3) shows that coffee is found outside of the tolerable limitations set in our model. Almost 33% of garden coffee in Ethiopia is found outside of the tolerable bioclimatic limits set (Fig. 3.9). Although a decline in tolerable locations is observed, the evidence from the actual area harvested shows that the coffee production has continued to increase in the majority of countries studied. Given the economic potential of coffee, the planted areas may have extended into highly managed marginal lands, with the infrastructure to adapt to climatic changes (Soini, 2005; Ambinakudige, 2009).

3.4.4 Limitations

There are several approaches to bioclimatic envelope modelling, and all have different limitations in their ability to model the distribution of species (Guisan and Zimmerman, 2000; Beaumont *et al*., 2007). To identify the number and location of optimal and tolerable coffee growing locations across the eight East African countries investigated, a physiologically based approach was used, relating climatic data with known climatic thresholds of coffee, to produce an expected bioclimatic envelope (Pearson and Dawson, 2003; Kearney and Porter, 2009). This method and approach was adopted as there was a lack of detailed coffee distribution data available (You *et al*., 2009).

A physiologically based model is representative of the fundamental niche of a species, and does not consider the non-bioclimatic constraints of current species distributions (Pearson and Dawson, 2003). An alternative approach to modelling species distribution involves the correlation of environmental variables with current species distributions based upon present-absence data, and this is more representative of the present-day realized niche (Huntley *et al*. 1995; Pearson and Dawson, 2003; Giordono *et al*., 2010). This approach results in a modelled distribution of a species, which incorporates non-climatic factors affecting species ranges, such as inter-specific competition and dispersal (Davis *et al*., 1998; Penman 2010).

A physiological based model over predicts the number of suitable growing sites, as species tend not to realise their full, potential fundamental niche (Pearson and Dawson, 2003). In Ethiopia, coffee growing sites fall within a far more defined climatic limitations, than are set by the bioclimatic envelope model used (Fig. 3.9). The tolerable precipitation limit is far beyond the actual maximum precipitation for coffee (Table 3.3). This will have resulted in an over estimation of coffee growing sites.

Bioclimatic envelope models have a number of limitations, including, no consideration for species dispersal mechanisms, evolutionary change, land-management changes, and inter-specific competition (Pearson and Dawson, 2003; Beaumont *et al*., 2007; Penman *et al*., 2010; Yates *et al*., 2010a). They do however provide a reliable estimate into the likely distribution of a species based on several climatic variables at a scale of above $10km^2$ (Guisan and Zimmerman, 2000; Pearson and Dawson, 2003; Thuiller *et al*., 2005).

3.5 Conclusion

Mean annual temperatures have increased and total precipitation has declined in all eight East African countries studied over the past 40 years. This change to a hotter and drier environment has coincided with a decline in both the number of optimal and tolerable arabica coffee growing locations across the region. The actual area of coffee harvested has declined over the period studied, but individual countries show differing trends.

At the present day, most locations in the East African region studied are too warm and too dry to be considered optimal locations for arabica coffee. Approximately 40% of locations included in the study are too dry to be classified as tolerable sites. If the trends from the past 40 years continue, and the climate becomes increasingly hot and dry, the number of optimal and tolerable locations will decline further. At the present day, there are only a handful of sites that are too cool for suitable arabica coffee production.

Zambia has lost the highest number of optimal locations over the period studied, and the central region of the country is the worst affected. The decline in the number of tolerable locations has been greatest in Ethiopia, and in particularly in the Southwest of the country. These countries were not identified as having experienced the greatest changes in precipitation or temperature, suggesting that there are other factors affecting the success and scale of coffee production. Only a few new areas have become suitable for arabica coffee over the past four decades, suggesting that if the climate continues to change, the future suitability of arabica coffee in East Africa could be threatened.

The bioclimatic model was validated against the known locations of present day garden and forest coffee in Ethiopia, and we concluded that the model is successful at predicting actual coffee growing locations. It over estimated the number of suitable locations because the model was based on physiological limits of arabica coffee, obtained through a literature research. The model did not consider abiotic factors that influence the distribution of arabica coffee in East Africa.

The number of optimal and tolerable locations can infer the suitability of arabica coffee in a particular region, but the number of locations may not necessarily be an indicator of yield. In the next section we examine the relationship between past mean annual temperature, precipitation, and actual country-level arabica coffee yields.

Chapter 4

The effect of climatic changes on arabica coffee yields in East African countries

4.1 Introduction

4.1.1 Climatic changes and crop yields

Several studies have begun to assess the impact of climatic changes on major food crops at a global scale (Parry *et al*., 2004; Porter and Semenov, 2005; Lobell and Field, 2007). Lobell and Field (2007) investigated the effects of changes in recent climate (1961-2002) on global yields of six key food crops (wheat, rice, maize, soy, barley and sorghum). They found that at least 29% of the variance in annual yields could be attributed to temperature and precipitation changes (Lobell and Field, 2007). Without climate change trends since 1981, production of wheat, maize and barley in 2002 would have been 2-3% higher than actually recorded (Lobell and Field, 2007). The results from Parry *et.al* (2004) support the above findings, and suggest that national cereal yields are likely to decline by up to 30% in developing countries by 2080.

The results of a multiple regression model show that coffee production in Veracruz Mexico, is expected to become uneconomical by 2020 (Gay *et al*., 2006). Studies have investigated the impact of climatic change on key food crops in East Africa, but there is little evidence of investigation into the changes in yield of high value agricultural crops such as coffee (Thornton *et al*., 2009). A future decline of coffee yields could greatly affect the economy of large producer countries (Gay *et al*., 2006; Eakin and Wehbe, 2009; Tucker *et al*., 2010), and the United Nations Development Programme expects that the success of the Ethiopian Coffee industry will be a key determining factor in Ethiopia achieving the Millennium Development Goals (Petit, 2007).

4.1.2 Empirical yield estimation models

Empirical yield estimation models are a relatively simple way to estimate the expected yield of a crop, over a large spatial area (Challinor *et al.,* 2009b). Such models parameterize crop yields, usually using climatic variables (Iglesias *et al*., 2002; Parry *et al*., 2004; Lobell *et al*., 2008). In Spain, a significant proportion of wheat yield variance was shown to be significantly correlated with precipitation anomalies during the growing season, and temperature anomalies between March and June (Iglesias *et al*., 2002). Correlation, and partial correlation coefficients between year-to-year changes of maximum temperature, minimum temperatures, averages temperature, diurnal temperature, precipitation and yield were calculated, and multiple linear regression models were used to determine the effect of climatic variables on Australian wheat crop yields (Nicholls, 1997). Lobell and Field (2007) used similar methods, running multiple liner regression models for six different crops as the dependent variable and first differences in minimum temperature, maximum temperature, and precipitation as the independent variables. They showed that higher mean annual temperatures negatively affect crop yields. One disadvantage of empirical models is their assumption of linearity for crop yields (Challinor *et al*., 2006). To overcome this problem, Gay *et al*. (2006) used quadratic regression models to determine the variables that most affect coffee yields in Mexico. They found that average summer temperature, average winter precipitation, and average winter temperature are the three climatic factors that most affect coffee productivity (Gay *et al*., 2006).

This chapter aims to establish the temporal patterns of arabica coffee yield in eight East African countries over the past 40 years. The relationships between annual yield and optimal and tolerable climatic conditions are considered, before determining which climatic factors can best explain variations in arabica coffee yields.

4.2 Methods

4.2.1 Temporal patterns of arabica coffee yield in East Africa

In Chapter 3 a general trend of declining climatic suitability for arabica coffee over the past 40 years in East Africa was identified. To establish if the decline in climatic suitability has led to a decrease in coffee yields, annual yields between 1961 and 2002 available from the FAO were analysed (FAO, 2009). For each country, calendar years were categorized as 'excellent', 'average' and 'poor' yielding years. These ratings were identified by calculating the upper (excellent) and lower (poor) quartiles of annual yield; years between the upper and lower quartiles were classified as 'average'. To determine if certain annual climate conditions coincided with excellent, average, and poor yielding years, the three categories were depicted in a 2D bioclimate space plot of mean annual temperature and total annual precipitation.

The months during which coffee is harvested varies between countries throughout East Africa (Table 4.1). Therefore, it is beneficial to analyse the data at a seasonal level, because annual climatic means may not determine productivity. Coffee may be more sensitive to seasonal climatic means and variation. Coffee is a perennial plant and yields produced in one year may primarily be the result of the previous years' climate (Willson, 1985). Yield classification plots were therefore produced showing the previous years' climate, and the resulting, 'excellent', 'poor' or 'average' yield classification. The calendar year is divided into seasons: March-April-May (MAM); June-July-August (JJA); September-October-November (SON); December-January-February (DJF). Seasonality coefficients were included in the analysis as climatic variability throughout the year is important for arabica coffee production, (e.g. a 12 weeks dry period is required, Descroix and Snoeck, 2004; Gay *et al*., 2006).

Table 4.1: The seasons and coffee harvesting months of East African countries. (Red cells show the warmest and wettest season, blue cells show the coolest, driest season). (EAFCA, 2009)

Country	Months coffee harvested	MAM Temp (ºC)	JJA Temp (ºC)	SON Temp (ºC)	DJF Temp (ºC)	MAM Precip (mm)	JJA Precip (mm)	SON Precip (mm)	DJF Precip (mm)
Burundi	February - June	19.8	19.4	20.3	19.8	433.8	36.6	318.8	369.9
Ethiopia	October - December	23.5	22.4	21.8	21.3	248.8	344.6	216.5	44.1
Kenya	April – June October - December	25.7	23.5	24.8	25.3	283.7	100.2	187.5	102.1
Malawi	April – September	22.0	18.8	23.7	23.6	355.1	22.0	96.6	683.4
Rwanda	March – June	18.2	17.9	18.1	18.1	400.5	107.6	370.7	301.3
Tanzania	July – December	22.7	20.7	23.2	23.3	428.1	39.2	155.0	425.6
Uganda	October - February August	23.5	22.1	22.7	23.5	366.7	300.6	350.4	124.2
Zambia	October - March	21.5	18.1	24.0	23.0	209.9	1.3	143.2	616.6

4.2.2 Climatic correlates of arabica coffee yields in East Africa

To determine the climatic variables that could explain the most variation in arabica coffee yields, Spearman's rho correlation coefficients were calculated and a series of multiple regression models were explored. All statistical analyses were performed in the programme *SPSS*. Coffee yield (recorded in Kg/Ha) was the dependent variable throughout the study, and the following climatic (independent) variables were investigated: mean annual temperature, seasonal mean temperatures, total annual precipitation, seasonal total precipitation, and a 3-year moving average of mean annual temperature and total precipitation. All variables were entered for both the present and previous year (year-1). First, second, and third order terms were entered for each climatic variable to represent a quadratic and cubic response between yield and climate, as crops do not respond linearly to climatic changes (Porter and Semenov, 2005; Gay *et al*., 2006; Tubiello *et al*., 2007). Including a quadratic and linear term for each variable can increase the problems associated with multicollineality so correlations between the independent variables were checked, using Variance Inflation Factor (VIF) analyses (Field, 2005; Gay *et al*., 2006). Multicollinearity exists when variables are very-closely linearly related, and a VIF value of >10 indicates that multicollinearity is a problem in the model (Field, 2005). Correlation coefficients between all climatic variables are included in Appendix Two, to show those variables that are highly correlated with one another.

Using the Kolmorgorov-Smirov test and values for skewness and kurtosis, non-normality was detected in a number of variables. Only MAM precipitation and total precipitation variables were normally distributed. Non-normally distributed variables were transformed using a using a $\log_{10}$ transformation. Correlation coefficients between yield and climatic factors were calculated at a country and regional (all country data combined) level. Multiple regression models were constructed at the regional level including all eight countries. Models were not established for individual countries because sample sizes, (41 years of data), were too small to produce accurate results given the number of independent variables used. Uganda was excluded from the regression analysis because only 6% of coffee produced in the country is of the arabica variety (EAFCA, 2009).

Initially, a series of exploratory models were constructed to determine if annual, seasonal, or 3-year moving averages of annual climatic variables are more influential in determining arabica coffee yield. All climate variables were entered into the model at the same time. Three families of models were built: one with annual variables, one with seasonal variables, and one with 3-yr moving averages of annual climatic variables.

The best series of models were determined by the adjusted R^2 value (the adjusted R^2 takes the number of variables into account) and the F-Ratio, as in the study of Spanish wheat yields (Iglesias *et al*., 2000). The closer the adjusted R^2 value is to one, the more variance is explained, using the smallest number of variables (Field, 2005:171). The F-ratio is a measure of the variance explained by the model and the inaccuracies that still exist in the model.

In the second stage of modelling, a stepwise variable selection procedure, including all variables plus their second and third-order factors, was run. In the stepwise procedure, the process of variable exclusion and inclusion leads to the model that explains most of the variation in the response variable, while using as few variables as possible (Field, 2005). The best model was again determined by the adjusted R^2 value.

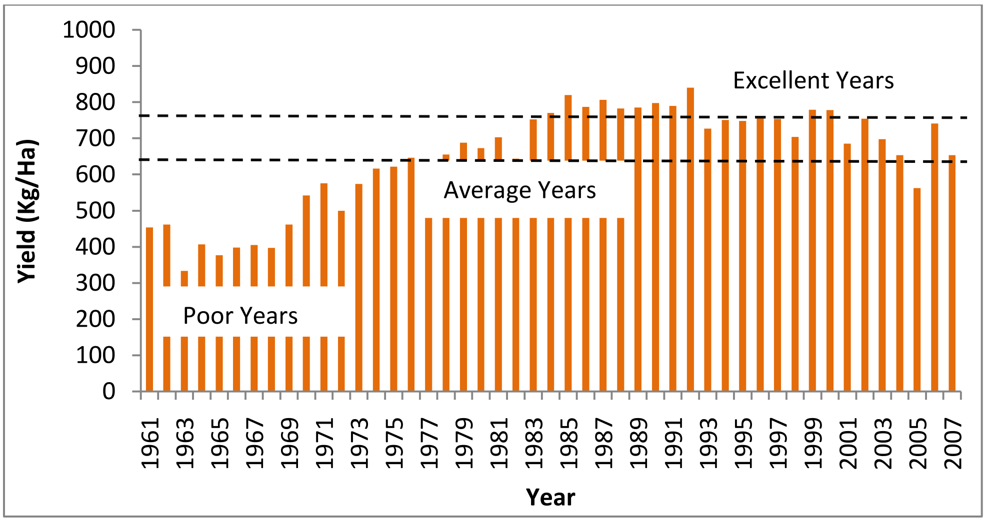
4.3 Results

4.3.1 Temporal trends in the yields of arabica coffee in East Africa

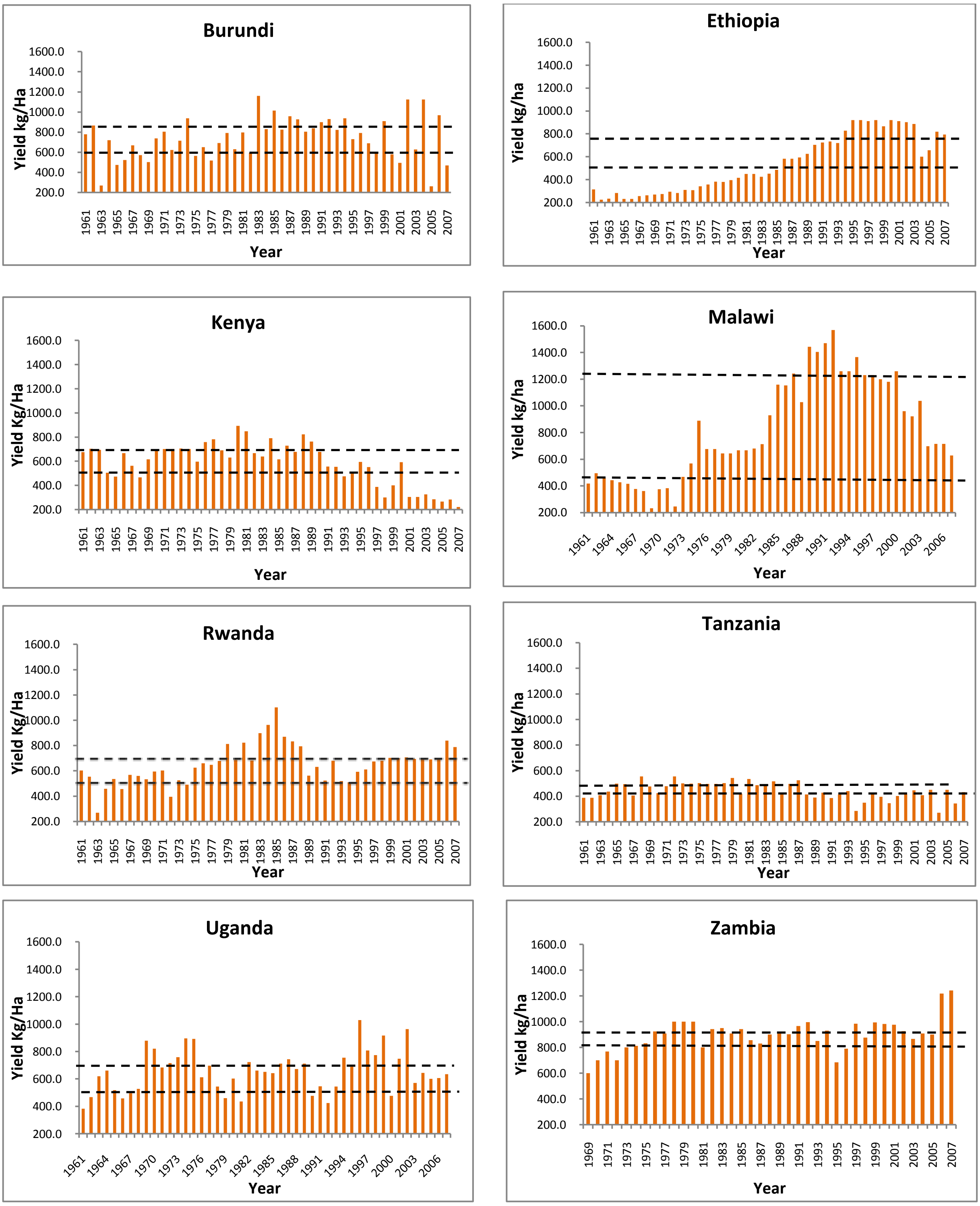
At the regional level, mean arabica coffee yields increased from 1961 until the mid-1980s, when a plateau was reached, before yields began to decline in the late 1990s (Fig. 4.1 a). All of the years with yields in the lower quartile are found in the first decade of the study period between 1961 - 71 (Fig. 4.1 a). Individual countries show a variety of trends (Fig. 4.1b).

Tanzania has consistently low yields, and the smallest range of yields through time, ranging from 240Kg/Ha to 550Kg/Ha (Fig. 4.1 b). Malawi has the greatest range of yields, and also the highest coffee yield of any country, with 1570Kg/Ha recorded in 1992 (Fig. 4.1 b). Ethiopia has the largest increase in yields over the time period studied, with around 230Kg/Ha recorded in the early 1960s, rising to over 900Kg/Ha during the 1990s.

Burundi, Kenya, Malawi and Tanzania all show a rise in yields from the 1960s to the mid 1980s/early 1990s, after which a decline in yield is observed. Although rising for longer, and into the late 1990s, Ethiopia also shows a decline in yield after 2000. Rwandan coffee yields peaked in the early 1990s, fell during the mid-late 1990s, and have begun to rise again during the last decade (Fig. 4.1 b). Zambia shows a rise in yields during the early 1970s, after which yields plateau at a relatively constant level of around 850Kg/Ha. The last two recorded years (2006 and 2007) show a rise in yields in Zambia (Fig. 4.1 b).



a)



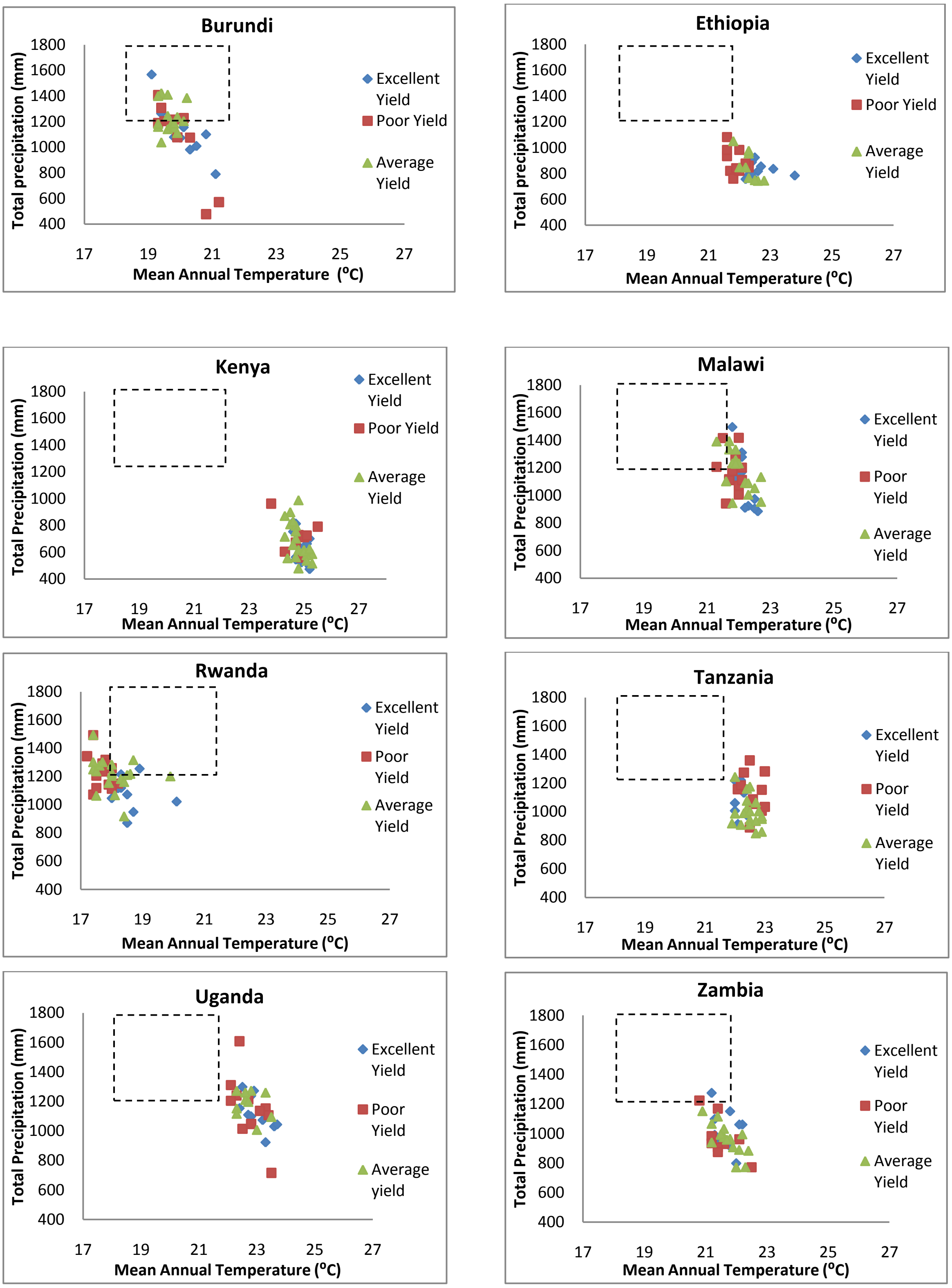
b)

Figure 4.1: a) Mean annual yields of arabica coffee in all East African countries studied excluding Uganda, and b) annual yields of arabica coffee by country. Dotted lines indicate the upper and lower quartiles.

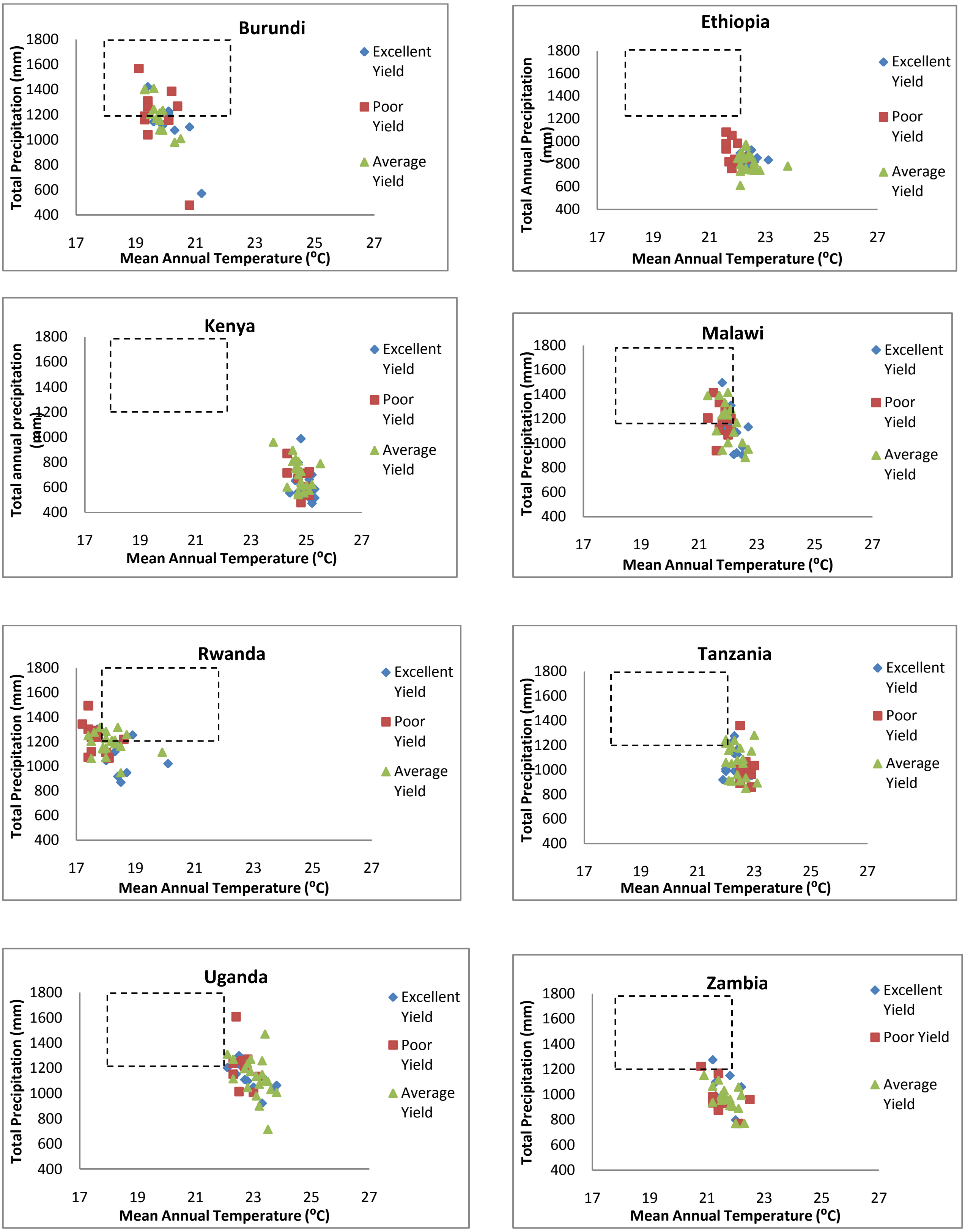
Arabica coffee is grown in all eight East African countries studied, but the bioclimatic space of each of the countries studied varies (Fig. 4.2). Rwanda has a mean annual temperature of around 17°C, while the mean annual temperature in Kenya is approximately 25°C (Fig. 4.2). Kenya has low total annual precipitation (approx. 600mm per year) in comparison with Burundi and Malawi, with around 1200mm per year (Fig. 4.2).

Malawi and Burundi are the only countries that have mean annual temperatures and total annual precipitation values that lie within the optimal conditions (18°C to 22°C and 1200mm to 1800mm) identified through the literature (Wrigley, 1988; Descroix and Snoeck, 2004). These countries do consistently produce the highest yields of the countries studied, suggesting that optimal climatic conditions do affect coffee yields (Fig. 4.1b).

In the majority of countries studied, including Kenya, Malawi, Uganda and Zambia, mean annual temperatures and total annual precipitation produce very mixed yield classifications, with no clear climatic thresholds defining ‘excellent’, ‘average’ or ‘poor’ yields. This indicates that factors other than mean annual temperature and total precipitation influence yield variation.


Burundi
Total precipitation (mm)
1800
1600
1400
1200
1000
800
600
400
17
19
21
23
25
27
Mean Annual Temperature (°C)
Excellent Yield
Poor Yield
Average Yield
Ethiopia
Total precipitation (mm)
Mean Annual Temperature (°C)
Excellent Yield
Poor Yield
Average Yield
Kenya
Total Precipitation (mm)
Mean Annual Temperature (°C)
Excellent Yield
Poor Yield
Average Yield
Malawi
Total Precipitation (mm)
Mean Annual Temperature (°C)
Excellent Yield
Poor Yield
Average Yield
Rwanda
Total Precipitation (mm)
Mean Annual Temperature (°C)
Excellent Yield
Poor Yield
Average Yield
Tanzania
Total Precipitation (mm)
Mean Annual Temperature (°C)
Excellent Yield
Poor Yield
Average Yield
Uganda
Total Precipitation (mm)
Mean Annual Temperature (°C)
Excellent Yield
Poor Yield
Average yield
Zambia
Total Precipitation (mm)
Mean Annual Temperature (°C)
Excellent Yield
Poor Yield
Average Yield

a)



b)

Figure 4.2: Characteristics of annual coffee yield in relation to mean annual temperature and total precipitation in a 2D climate space. The dotted line shows the optimal growing conditions for *C. arabica*. In part a) annual yields are used to determine the yield classification and in part b), yield + 1 year are used, to account for coffee harvested in different calendar years.

Table 4.2: Spearman Rho Correlation Coefficients of annual and seasonal climatic variables and arabica coffee yields in East Africa.

	Burundi	Ethiopia	Kenya	Malawi	Rwanda	Tanzania	Uganda	Zambia	East Africa
Annual variables:									
Mean Annual Temperature		0.66		0.51	0.58	-0.39			-0.16
Mean Temperature Yr – 1	0.47	0.64		0.49	0.51	-0.55			-0.17
Total Annual Precipitation					- 0.48				
Total Precipitation Yr - 1					0.40				
Seasonal Temperature variables:									
MAM Temp		0.56		0.51	0.53	-0.32			-0.24
MAM Temp Yr – 1	0.48	0.50		0.50	0.45	-0.35			-0.24
JJA Temp	0.32	0.69		0.41	0.52	-0.45			-0.29
JJA Temp Yr – 1	0.44	0.68		0.39	0.56	-0.67			-0.30
SON Temp		0.46			0.51				0.13
SON Temp Year – 1	0.43	0.49			0.60	-0.44	0.32		0.14
DJF Temp		0.45		0.44	0.38				
DJF Temp Yr – 1		0.50		0.44	0.33	-0.40	0.38		
Seasonal Precipitation variables:									
MAM Precip					-0.34				-0.14
MAM Precip Yr – 1									-0.17
JJA Precip				-0.57					-0.35
JJA Precip Yr – 1	-0.38			-0.51					-0.37
SON Precip									
SON Precip Year – 1							-0.33		
DJF Precip									0.29
DJF Precip Yr – 1									0.28
3-yr average annual variables:									
3-Yr Average Temperature	0.45	0.82		0.72	0.61	-0.57			-0.17
3-Yr Average Total Precipitation	-0.34	-0.43		-0.32	-0.62			0.35	

Only significant values p<0.05 are shown.

4.3.3 Estimating yields of arabica coffee using mean climatic variables

From the initial exploratory models it was found that seasonal climatic variables explained more yield variation than annual climatic variables, which supports the results from the Spearman's Rho correlation coefficients (Table 4.2 and 4.3).

Table 4.3: Explaining the variation of arabica coffee yields: the significance of seasonal and annual climatic variables

Independent Variables	First Order		Second Order		Third Order	
	Adjusted R^2	F-Ratio	Adjusted R^2	F-Ratio	Adjusted R^2	F-Ratio
Annual Climatic Variables	0.001	1.11	0.001	1.10	0.005	1.78
Annual Climatic Variables Yr^{-1}	0.000	1.00	0.070	1.00	0.006	1.85
Seasonal Climatic Variables	0.210	10.19*	0.210	10.26*	0.200	9.89*
Seasonal Climatic Variables Yr^{-1}	0.220	10.84*	0.210	10.20*	0.220	10.92*
Three Year Average Climatic Variables	0.001	1.20	0.002	1.23	0.002	1.34

*Values are significant at the 0.05 level (2-tailed)

The best model was obtained using the values of the third order seasonal year-1 climatic variables, which explained 22.2% of yield variation. Generally the year-1 exploratory models explained more yield variation that current year variables, and this supports the correlation coefficients in Table 4.2. This suggests that the climate of the previous year affects coffee yields, more than the present year.

The results of the 'stepwise' modelling process, which involved all climatic variables being entered into a regression model, to identify those variables that could explain some of the variance in yield, resulted in two significant models were identified. The best model could account for 22.6% of the yield variation observed (Table 4.4). The model shows that the third order JJA mean temperature of the previous year explains most of the variance in yield, with the second order MAM precipitation variable also significant. The information on seasonality supports these results, as JJA is the coldest season in all countries except Ethiopia and MAM is the wettest season in all countries except Ethiopia, Malawi, and Zambia, resulting in high sensitivity for these seasons (Table 4.1).

Table 4.4: The results of the stepwise model using yield as the dependant variable and seasonal and annual climatic variables as independent variables

Model Number	Variables Entered	R^2	Adjusted R^2	F Ratio (Sig)
1	Third Order JJA Temperature Year^{-1}	0.219	0.216	79.53 *
2	Third Order JJA Temperature Year^{-1}, Second Order MAM Precipitation	0.231	0.226	42.57 *

*Values are significant at the 0.05 level (2-tailed)

A high number of independent variables are significantly correlated, and the correlation coefficient (-0.16) between order JJA temperature and MAM precipitation is significant (Appendix Two).

4.4 Discussion

4.4.1 Climatic variation and arabica coffee yields

The yields of arabica coffee vary in time both within, and geographically between each of the eight East African countries (Fig. 4.1). Some of this variation can be explained by climatic variables (Table 4.4). Generally a rise in yields has been observed since the 1960s, but this has been followed by a decline over the last decade (Fig. 4.1). These results are similar to other studies which have shown a decline in crop yields n East Africa over time (Ingram *et al*., 2008).

Climatic variables (JJA temperature and MAM precipitation) can account for some of this variation in arabica coffee yield (Table 4.4), but there was no clear climatic signal in distinguishing 'excellent', 'average' and 'poor' yield years. Possible explanations for this could include: countrywide mean annual temperature and total annual precipitation values are too generic to predict resulting arabica coffee yields, and/or there are other non-climatic factors that influence yields.

The results of the Spearman’s Rho correlation coefficients and the regression models show that seasonal climatic variables are more significant in explaining variations in yield, than annual climate variables in our study of arabica coffee in East Africa (Tables 4.2. 4.3, and 4.4). Results from previous studies support these findings indicating that coffee is sensitive to seasonal fluctuations, and the success of coffee depends upon the timing of rainfall, and specific temperatures throughout the year

(Willson, 1985; Wrigley, 1988; DaMatta, 2004). In studies of other East African food crops, seasonal climatic variables have been reported to be significant in determining yield. High summer temperatures in Kenya negatively affect crop production, while high winter temperatures benefit yields (Dinar *at al*., 2008). Increasing precipitation during winter months in Ethiopia reduces crop productivity, while summer precipitation increases crop yields (Dinar *et al*., 2008).

Results of the regression model showed that the third-order value of the previous year JJA temperature and the second-order MAM precipitation are the two most significant climatic variables (Table 4.4). These results are comparable with other studies of arabica coffee, which found the average summer temperature, the square of the average summer temperature, average precipitation during spring, the average winter temperature, the square of the average winter temperature, and the real minimum wage significant in determining the production of coffee in Mexico (Gay *et al*., 2006). These authors did not include values for the previous year's climate in their models. JJA temperature could be expected to be a significant determinant of yield, as it is typically the coolest season in East Africa, and MAM is the wettest (Funk *et al*., 2008).

The regression model can explain 22.6% of the variation in arabica coffee yields (Table 4.4). Compared to other crop yield regression models, which have resulted in models explaining at least 30% of yield variation, the model has a low adjusted R^2 value (Nicholls, 1997; Iglesias *et al*., 2000; Lobell *et al*., 2007). The lower R^2 value may be a result of the coarse spatial resolution of data used in the model, and specific socio-economic factors linked with coffee production and the East African region. Given the low adjusted R^2 value obtained from the multiple regression model it is concluded that the model using third order JJA temperature year^{-1} and second order MAM precipitation is unsuitable for use in predicting arabica coffee yields.

4.4.2 Non-climatic variables affecting yield

Arabica coffee growing in East Africa is affected by many socio-economic variables, which, in turn, affect yield variation. Coffee yields and the world coffee price are closely related: for example, when yields are high and there is a lot of coffee entering the market, prices of coffee fall (Petit, 2007; Ghosray, 2010). This can make production for smallholder farmers uneconomical and prevent land owners harvesting ripe coffee cherries (Eakin *et al*., 2005). If coffee is not harvested annually, productivity of a coffee plant declines, producing inferior quality and lower yields in subsequent years (Wrigley *et al*., 1988; Teketay 1999).

The management of coffee growing systems greatly affects yields. In Ethiopia, forest coffee systems produce yields of around 200kg per ha, while garden coffee or plantation coffee yields are between 450kg - 750kg per ha (Petit, 2007). Harvesting practices will affect yields, and higher yields are obtained from mechanised harvesting systems (Petit, 2007). Coffee is regularly grown under shade, and is planted alongside a second economically viable crop, such as bananas or groundnuts (Cannell, 1985; DaMatta, 2004; Lin, 2007). Although protecting coffee plants from high temperatures, these shade crops can compete for nutrients and water. The planting density of coffee varies, and studies have shown that closer planting can result in increased yields, until a threshold of 2000 trees per ha, when yields decline due to shading (Cannell, 1985).

Fertilizer usage in most of East Africa is minimal, although some larger commercial plantations have access to fertilizers and insecticides to increase coffee yields (Petit, 2007). Access to fertilizers has greatly increased over the past 40 years, which may have accounted for some of the yield increases observed in managed crops (Lobell and Field, 2007; Petit, 2007). Depending upon the coffee system used to cultivate coffee, climatic variables will have differing impacts upon yield.

Coffee yields are affected by coffee pests and diseases, which may or may not be caused by climatic variations (Rutherford, 2006). Coffee wilt disease is particularly prevalent in East Africa, and during the late 1990s, coffee wilt disease became endemic in all coffee producing areas in Ethiopia (Rutherford, 2006). This may have contributed to the decline in coffee yields observed in Fig. 4.1. Coffee berry disease also threatens Ethiopian coffee in 50-60% of production areas (Petit, 2007).

Variations in yield are increasingly determined by the number, and diversity of, pollinators (Klein *et al*., 2003). In an Indonesian study, the coffee fruit yield increased when bee diversity increased from three to 20 different species (Klein *et al*., 2003). Insect pollinators are important for fertilisation of arabica coffee, so changes in climatic variables or disease persistence that threaten pollinators can affect coffee yields (Descriox and Snoeck, 2004).

Land use, population pressure, and work force availability all affect coffee yields. In Tanzania, where coffee yields have been low (Fig. 4.1), population increase has forced marginal land to be used in agricultural cultivation (Soini, 2005). Turning forested areas into agricultural land can result in increased pressure on natural resources, altering water run-off and increasing soil degradation, resulting in lower crop yields (Ambinakudige and Choi, 2009). Coffee is a labour intensive crop, and requires a large work force, especially when farmed in smallholdings and coffee forests as in East Africa (Petit, 2007). Labour availability in East Africa is determined by the health of the population, food security, and economic factors which influence the migration of the workers (Schmidhuber and Tubiello, 2007). If the availability of labour declines, coffee yields fall (Petit, 2007; Eakin *et al*., 2009).

In summary, coffee and the East African region are particularly vulnerable to socio-economic changes and therefore climatic variables can only determine a small level of variation in crop yields (Slingo *et al*., 2005). This may explain that although the model showed some linkages between mean climatic variables and yield, it was not able to account for all of the variability. Management practices may explain the trend of declining areas of climatic suitability for arabica coffee, but increasing yields.

4.4.3 Methods of modelling crop yields

A wide variety of techniques and methods have been utilised in previous studies to determine the spatial distribution of crops, and relationships between climatic variables, management systems, and crop yields (Stockle *et al*., 2003; Stehfest, 2007; Liu *et al*., 2008; You *et al*., 2009). Although there are many techniques, many were unsuitable for use in this study. Possible crop modelling systems are discussed and evaluated for use in this study below.

CropSyst is a model tested and evaluated over a numbers of crop species in different locations throughout the world, and serves as an analytical tool to study the effect of climate, soils, and management (Stockle *et al*., 2003; Moriondo *et al*., 2007). It is intended for crop growth simulations over a single land fragment with uniform soil, weather, crop rotation and management, and therefore classified as unsuitable for use in this study, which sought to investigate arabica coffee distribution and climate relationships with yield, over a large, continental region (Stockle *et al*., 2003).

The DayCent and CERES model families are designed to simulate agricultural and natural ecosystems, but both require significant parameterisation and calibration, in addition to detailed input data, including planting dates, soil properties and daily solar radiation (Stehfest, *et al*., 2007; Thornton *et al*., 2009). Although proven to well-replicate the observed yields of rice, wheat, and maize, neither have been used to model arabica coffee yields and the required level of input data for successful simulations was not available.

In a study to identify areas of Sub-Saharan Africa that are at risk from future food security issues, Liu *et al*. (2008), used the biophysical model, GEPIC. This model stimulates spatial and temporal dynamics of agricultural production and related processes, such as weather, hydrology, nutrient cycling, tillage, plant environmental control, and agronomics (Liu *et al*., 2008). It is underpinned by a crop growth model, and requires input data including, information on location, climate data, soil physical parameters, land use data, plant parameters and management data, including irrigation and fertilizer application (Liu *et al*., 2007). While GEPIC has been shown to produce accurate distributions for a number of food crops (Liu *et al*., 2008), the detail of input data required (such as slope, elevation and solar radiation information), makes the use of the model beyond the scope of this study.

Although successful at modelling some species of crops, the above modelling techniques were considered unsuitable for this study. Methods involving statistical models such as those used by Iglesias *et al*. (2000), and Lobell and Field (2007), were deemed more appropriate in determining the impact of climatic variables on arabica coffee yields and therefore utilised in this study.

4.4.4 Limitations

Although an empirical approach to modelling was deemed the most appropriate for this study, there are a number of limitations in the methods used, and improvements that could be made.

The results from the Spearman's Rho correlation coefficients on a country level show that different seasonal variables are highly correlated with yield within each country (Table 4.2). The regression models used average values for all climatic variables across the eight East Africa countries studied, rather than separate models for each country. A region-wide modelling method was used as this ensured that, if a successful model was found, it could be readily applied to predicting future yields in all eastern Africa countries. If models for each individual country had been identified, these may have had a high predictive capacity for that region, but may not have been applicable over larger areas. If the future climate changes, the relationship between climatic variables may alter, and the climate of one country, may become more similar to the current climate of a different country, but this would not be reflected in an individual country model. This problem is exemplified in a study conducted by Dinar *et al*. (2008), which showed that the same changes in temperature and precipitation, will affect crop yields differently in the Highlands and Lowlands of Kenya.

The spatial resolution and unavailability of the data used will affect the accuracy and ability of the models to predict coffee yields. For example, because of the lack of data, it was not possible to investigate regional variations within countries. Instead, country-wide yield, temperature, and precipitation data represented the highest resolution that could be acquired. Given the political framework of East Africa, the reporting mechanism for recording yields are likely to vary from one country to another. Some of the yield data used are best estimates calculated by the FAO (FAO, 2009).

There are many other climatic variables that determine and influence coffee yields, other than mean temperatures and total precipitation. Wind affects evapotranspiration, alters humidity and moisture availability, and strong winds can damage plants (Willson, 1985; Teketay, 1999, DaMatta, 2004). Light intensity controls the rate of photosynthesis and plant productivity (Willson, 1995). Large diurnal temperature ranges negatively affect coffee yields but this study does not consider daily temperature variation (DaMatta, 2004). Water availability is determined by the soil water capacity, and coffee can survive and produce high yields in regions with low annual precipitation, but high soil water capacity (Willson, 1985).

Future improvements to the model could include a variable measuring climatic variability, such as standard deviation of mean temperatures and precipitation (Gay *et al*., 2006; Block *et al*., 2008).

4.5 Conclusion

This chapter has shown that coffee yields have varied throughout East Africa over the past 40 years, with a peak in mean yields during the late 1980s. Model results show that seasonal climatic variables have a greater influence on yield variation than annual variables, and that the seasons of MAM, and JJA are generally the most significant in determining yields. Each country is affected differently by different seasonal variations, but for the region as a whole, third order JJA temperatures of the previous year, and the second order MAM precipitation variables, could explain 22.8% of the annual variation in yield.

The level of variance explained by the model is generally low, and 80% of yield variance is unaccounted for by this model. Coffee yields are affected by a large number of other factors including world coffee price, land management, availability of pollinators, prevalence of plant diseases, and the presence of a healthy workforce. These environmental and socio-economic factors account for a large amount of variation in arabica coffee yields, but are not quantified in the model.

Using the results from Chapter 3, and the insight gained from this chapter on the significance of seasonal climatic variables, Chapter 5 will predict the future distribution of climatically suitable areas for arabica coffee in East Africa.

Chapter 5

Future areas of climatic suitability for *Coffea arabica* in East Africa

5.1 Introduction

The successful development and production of plants is dependent upon a wide range of factors, and climate plays a key role in determining plant productivity and suitability to a particular environment (Slingo *et al*., 2005; Lobell and Field. 2007). As the future climate changes and new climatic trends emerge, it is expected that species will respond resulting in different distributions and levels of productivity (Slingo *et al*., 2005; Brown and Funk, 2008). An extensive number of studies over the past decade have begun to predict crop productivity and model expected species' range and distribution (Lobell and Field, 2007; Lobell *et al*., 2008; Ortiz *et al*., 2008).

Using a range of techniques, including bioclimatic envelope modelling, numerous studies have modelled future land-use and potential species distributions. For example, using bioclimatic envelope models, Wisz *et al*. (2008) showed that the Netherlands and Germany could lose up to 50% of the grasslands that are presently suitable for *Anser brachyrynchus* (pink-footed goose) grazing. Up to 80% of cropland areas (used for food production) in parts of central Spain, Northwest France, eastern England and southern Italy could be lost to different land-uses by 2080 (Schroter *et al*., 2005). By 2050, climatic shifts in the Indo-Gangetic Plains, currently a high wheat producing region, could make up to 51% of the land area heat stressed, reducing yields, unless alternative crop managements systems are utilised (Ortiz *et al*., 2008).

The results from a large number of global circulation models generally predict Africa to become warmer and wetter over the next century (Challinor *et al*., 2007; IPCC, 2007). These changes in climate are expected to result in a shift in tropical broadleaved evergreen and tropical broadleaved rain green trees, at the expense of C4 grasses (Doherty *et al*., 2010). In Egypt, the area planted under wheat is expected to decline as mean annual temperatures rise and the planting date of rice will become earlier to avoid a decline in productivity (Hegazy *et al*., 2008). By 2100 maize will be planted in different agricultural areas of Egypt in comparison to the present day, and earlier sowing will be required (Hegazy *et al*., 2008). Climatic changes could have major negative effects on wheat growing areas in the already dry areas of the South African Highveld (Walker and Schulze, 2008).

The productivity of crops will be affected by climatic change and yields from rain-fed agriculture could decline by up to 50% by 2080 (IPCC, 2007). Global cereal production is expected to decline by up to 10% by 2020 under the A2 emission scenario (Parry *et al*., 2004), but changes vary through space and time. The production of maize in South Africa could decline by 30% by 2030 (Lobell *et al*., 2007). Consistency between crop production models varies depending upon the parameters used, resulting in a range of results for any given region. Schlenker and Lobell (2010) forecast a decline in maize, sorghum, millet, groundnut and cassava across Africa, but Thornton *et al*. (2010), expects an overall increase in maize production across the region. Within countries, different areas may benefit from changing climatic variables; in Kenya bean production will rise by 17% by 2050 from 2005-2007 levels in mixed rainfed temperate/tropical highlands, but there will be no increase in rainfed humid/sub-humid regions (Thornton *et al*., 2010).

Sub-Saharan Africa is already vulnerable to climatic shocks, as many people live below the poverty line, GDP is low, and subsistence (low input) farming is widespread (Challinor *et al*., 2007; Thornton *et al*., 2009). With limited resources available, it is important to be able to forecast which areas of the region are most vulnerable to future climatic changes, so that adaptation and livelihood strategies can be developed in these areas.

This chapter aims to determine the future areas within East Africa that will be climatically suitable for arabica coffee cultivation in 2020, 2050 and 2080. To do this, the future climatic variables were derived from a number of global circulation models and a bioclimatic envelope model was used to identify the locations of climatically suitable areas.

5.2 Methods

5.2.1 Future climatic variables

There are a wide variety of general circulation models (GCMs) that can be used to derive future climatic variables, to use in predicting future species distribution and crop yields. Each model uses a different set of parameters to represent land-use scenarios, and key ecosystem processes, so there are obvious differences in the future predictions of climate between different climate models (Doherty *et al*., 2010). In this study, the HadGEM, Echam5, and CSIRO3 model were used to predict future climatic variables. These were chosen because each has been used in previous studies of the East African region (Conway *et al*., 2007; Doherty *et al*., 2010; Tabor *et al*., 2010). As in a number of other studies, three time-slices were used, based upon 30-year averages for 2020, 2050, and 2080 (Parry *et al*., 2004; Schmidhuber and Tubiello; 2007). Two greenhouse gas emission scenarios A1B and A2 were used (IPCC, 2007).

The A1B emission scenario assumes rapid future economic growth, low populations growth and a rapid introduction of new and more efficient technology. The A2 emission scenario is based upon a world of high population growth, less rapid economic growth but a highly heterogeneous world (IPCC, 2007). Mean monthly and annual values were derived for mean temperature and total precipitation. Direct outputs from the GCM's were used to derive future climatic variables, although in utilising this method, climate bias within the models was not accounted for. If each GCM was used to run to simulate the present-day climate, each would produce a unique set of results, different from the actual present day climate. The data for the present-day output for the GCM's used was not made available to us in this study.

All output from the climate models used, simulate the same seasonal variations as the present day climate, which was derived using used the CRU dataset. All models, including the output of the HadGEM model (which was also derived using CRU anomalies) show a large decline in precipitation for the present day to 2020, with increases in 2050 and 2080.

5.2.2 Identifying future climatically suitable areas

To identify the trends in future climate, and to observe changes in seasonal variability, plots were produced showing the monthly values of average temperature and total precipitation for each climate model, time slice and emissions scenario. These were compared with present day values, which were calculated from the most recent (1990 – 2002), time-slice available.

Utilising the same bioclimatic envelope approach as used in Chapter 3, the future climatically suitable regions for arabica coffee were mapped, based on optimal and tolerable annual temperature and total precipitation thresholds. Optimal locations were defined as areas that have a mean annual temperature of between 18°C - 22°C, and total annual precipitation between 1200mm - 1800mm. Tolerable locations have a mean annual temperature of 15°C - 30°C and total annual precipitation of 800mm - 2500mm. The change in the number of suitable locations between each of the future predictions and the present day (average of 1990-99 climatic variables) was then calculated. A bioclimatic envelope was used to predict the number of suitable coffee growing locations in 2020, 2050, and 2080.

Using the actual arabica coffee distribution maps for Ethiopia (shown in Chapter 3), the number of actual forest and garden coffee sites that will remain suitable for coffee production under the future scenarios were calculated. To determine if temperature or precipitation is the limiting factor in the number of optimal and tolerable cells, under each time-slice and emission scenario, the number of locations which fall within each of these thresholds for mean annual temperature and total precipitation was plotted.

5.3 Results

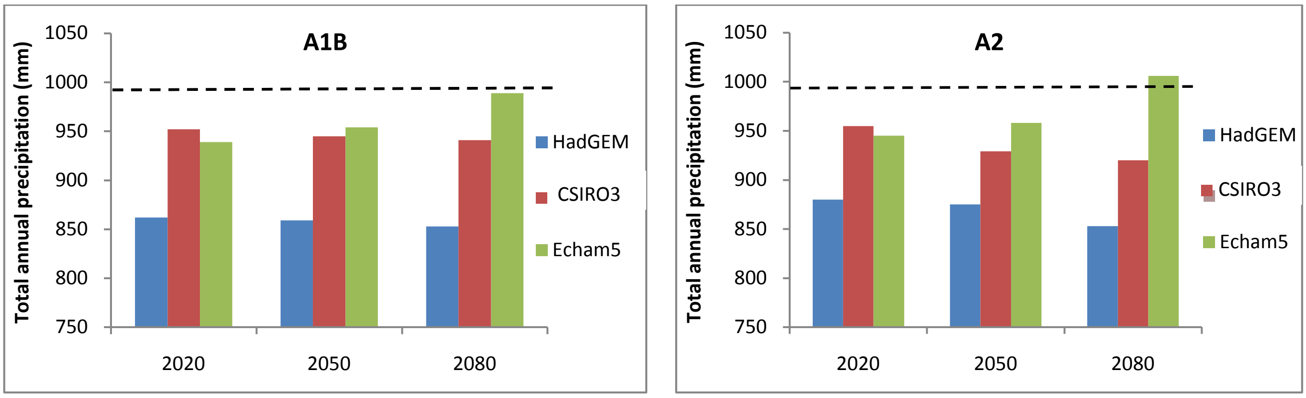
5.3.1 Future climatic trends

Over the time periods studied, all models except Echam5 under the A2 scenario in 2080 show a decline in the total amount of precipitation in East Africa. Generally, the decline is relatively small and, on average, is around 50mm for each 30 year time period studied (2020, 2050 and 2080) (Fig. 5.1 a). The exceptions to this are the results of the HadGEM global circulation model, which predicts a drier future then the other two models. By 2080, the HadGEM model results show a decline of 150mm of precipitation from the present day. All models show that the largest decline is between present day values of precipitation and those estimated for 2020. After 2020, the decline is less, and precipitation plateaus, only declining slightly from 2020 values by 2050 and 2080 (Fig. 5.1 a). This larger discrepancy between present day and 2020 climatic values may be accounted for by the climate bias in the models.

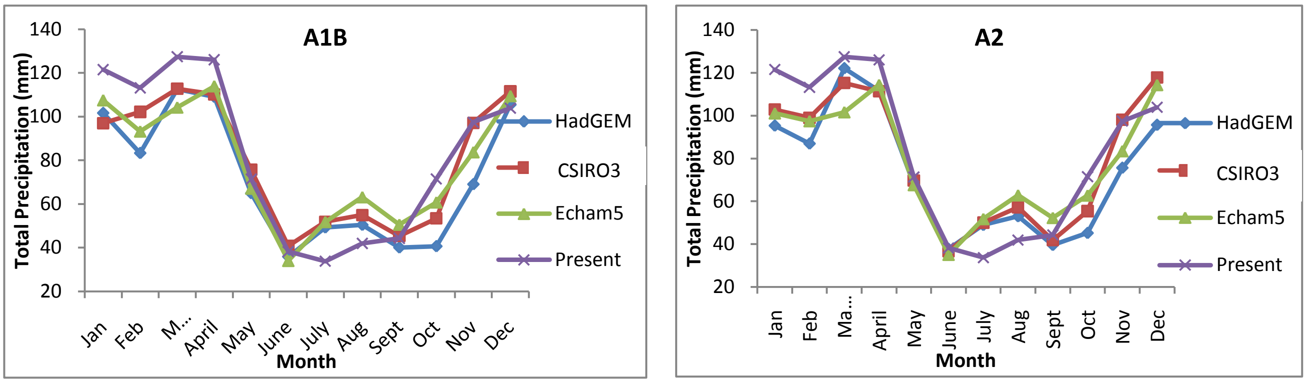
The seasonal variation and distribution of precipitation throughout the year changes through time, and is dependent upon the GCM used. In all times slices, emission scenarios studied, and GCMs used, June remains the driest month, except in 2050 under emission scenario A1B, when the HadGEM model estimates October to be the driest month (Fig. 5.1 b-d). Although June remains the driest month, the dry period in all the variations studied becomes much shorter, with average July and August precipitation doubling from the present day value of 20mm, to 40mm in the future (Fig. 5.1 b-d). In all time-slices, and under both emission scenarios, the HadGEM model predicts a drier September to December period than there is currently. Generally, there is little difference between the model estimates under the A1B and A2 scenarios.

The annual mean temperature rises in all future time-slices, (regardless of the GCM and emission scenarios used). The largest increase from the present day is seen in 2080, when annual mean temperatures can be expected to be 3°C to 4.5°C higher than present (Fig 5.2a). Under the A1B emissions scenario, both the HadGEM and Echam5 models show a similar trend and estimate rising annual temperatures, above those predicted by the CSIRO3 model. Under the A2 emissions scenario, the CSIRO3 model estimates a maximum mean annual temperature of 27°C in 2080, nearly 5°C warmer than the present day.

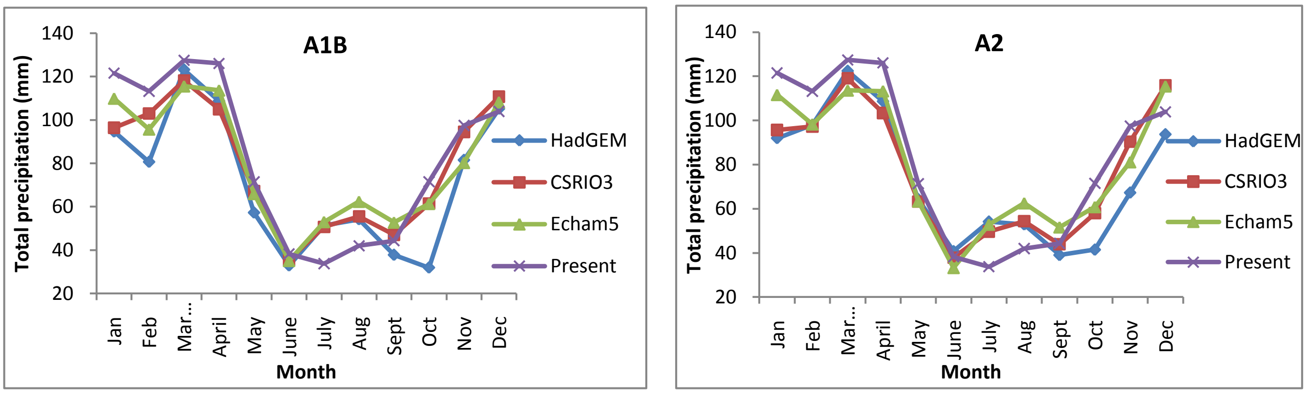
In 2020 and 2050, the monthly trends in temperature remain the same, with June to August the coolest months, and February-to- March and October-to-November the warmest months (Fig. 5.2 b-d). The HadGEM model under the A1B scenario shows a slight diversion to this, with June being the coolest month, but the temperature quickly rises to a high in September, which is 3°C - 4°C warmer than the present day. In 2080, under both the A1B and A2 emission scenarios, Echam5 shows the highest rise in mean annual temperatures. The coolest month is July (25.2°C under the A1B scenario and 25.6°C under the A2 emission scenario) and the warmest months are March and October (28°C) Fig. 5.2 d).



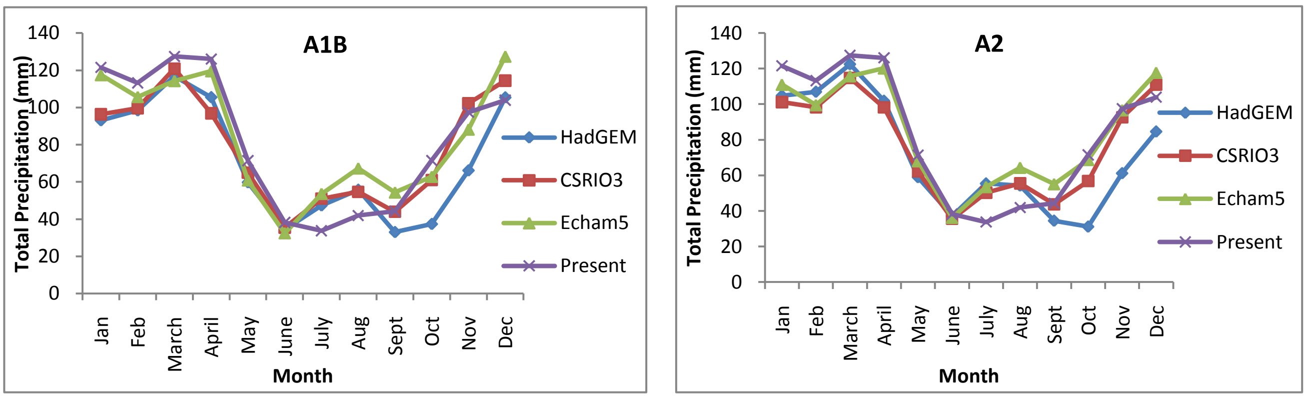
a) Predicted changes in total annual precipitation across all time slices according to three models. (Dotted line shows present total annual precipitation)



b) 2020

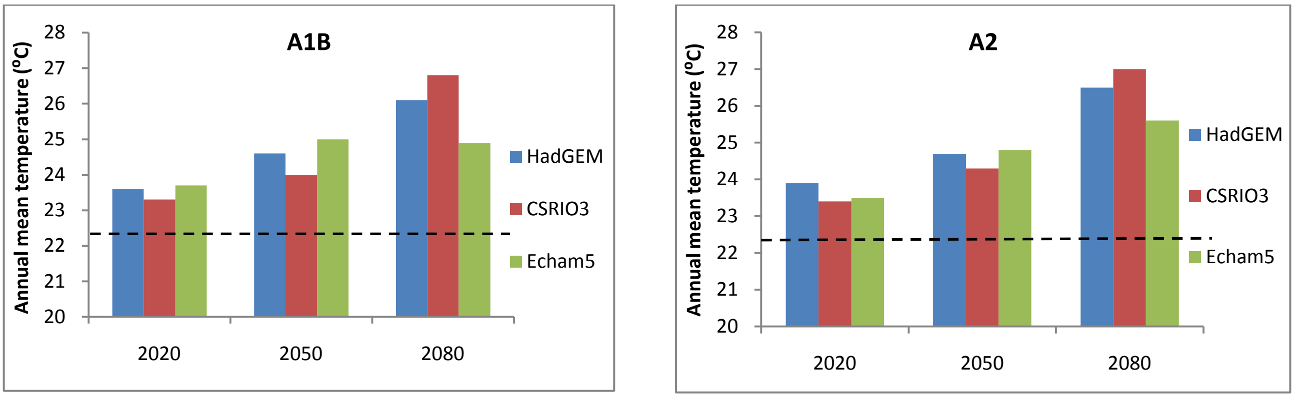


c) 2050

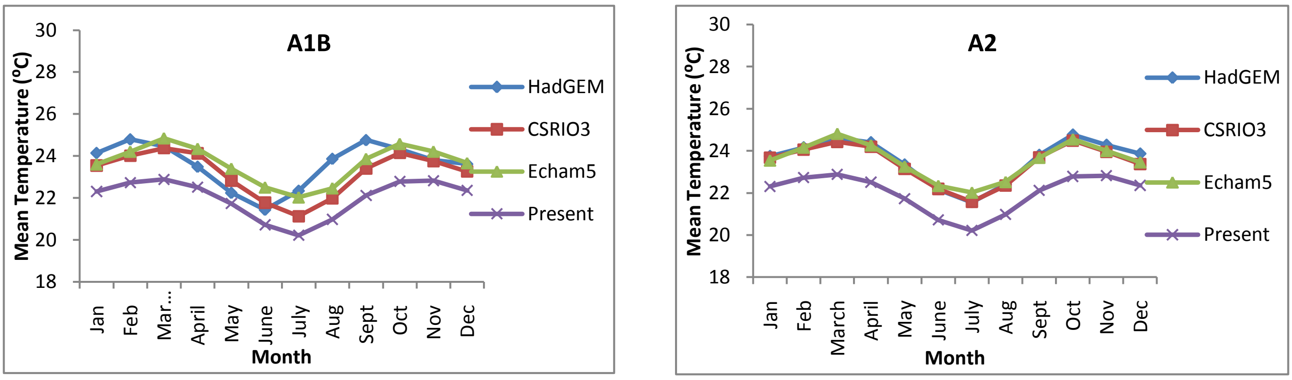


d) 2080

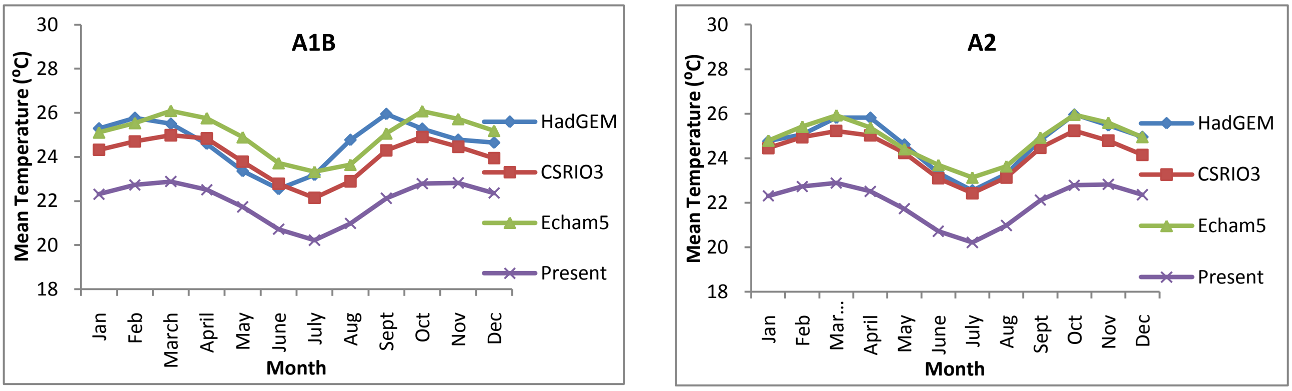
Figure 5.1: Monthly and total annual precipitation for present day, 2020, 2050 and 2080 using two different greenhouse gas scenarios (A1B and A2), and three different global circulation models



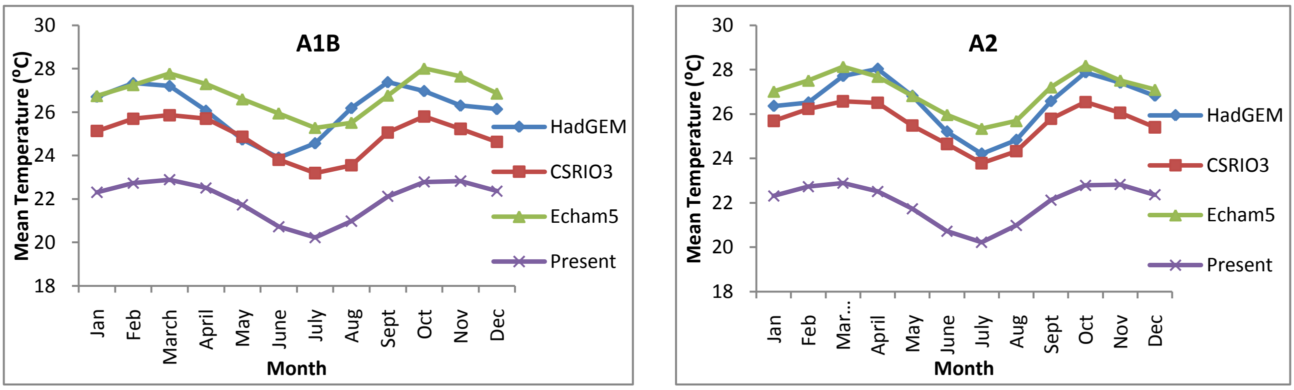
a) Predicted changes in mean annual temperature across all time slices according to three models. (Dotted line shows present total annual precipitation)



b) 2020



c) 2050



d) 2080

Figure 5.2: Mean monthly and annual temperatures for present day, 2020, 2050 and 2080 using two different greenhouse gas scenarios (A1B and A2), and three different global circulation models

5.3.2 Future climatic suitability of C. arabica in East Africa

During the 21st century, the effect of rising mean annual temperatures will be a shift in the climate space of terrestrial land cells within East Africa (Fig. 5.3). Based upon annual means, locations become hotter and drier across the region. By 2080, under the A2 scenario, the optimal envelope for arabica coffee is on the very edge of climate space, with mean annual temperature the limiting factor.

There is a consistent predicted decline in the number of optimal arabica coffee growing locations in East Africa post 2020 (Fig. 5.4). Under all GCMs, the expected number of optimal locations is less than 45 by 2080, a decline of almost 75% from 1960 (Fig. 5.4). The lowest number of optimal sites is predicted by the HadGEM model under the A2 emission scenario. Under this combination it is expected that just 19 sites will have optimal climatic conditions for arabica coffee growing, a decline of 80% from the present day.

The trend for the number of tolerable locations is less consistent, with the Echam5 and CSIRO3 model predicting an overall rise in the number of tolerable sites from the present day. The Echam5 model predicts that this rise will continue throughout the time period studied, but the CSIRO3 model suggests a peak in the number of tolerable sites in 2020, followed by a decline. The HadGEM model predicts a further decline, (up to 10% of the present day) of the number of tolerable locations during the next century (Fig. 5.4).

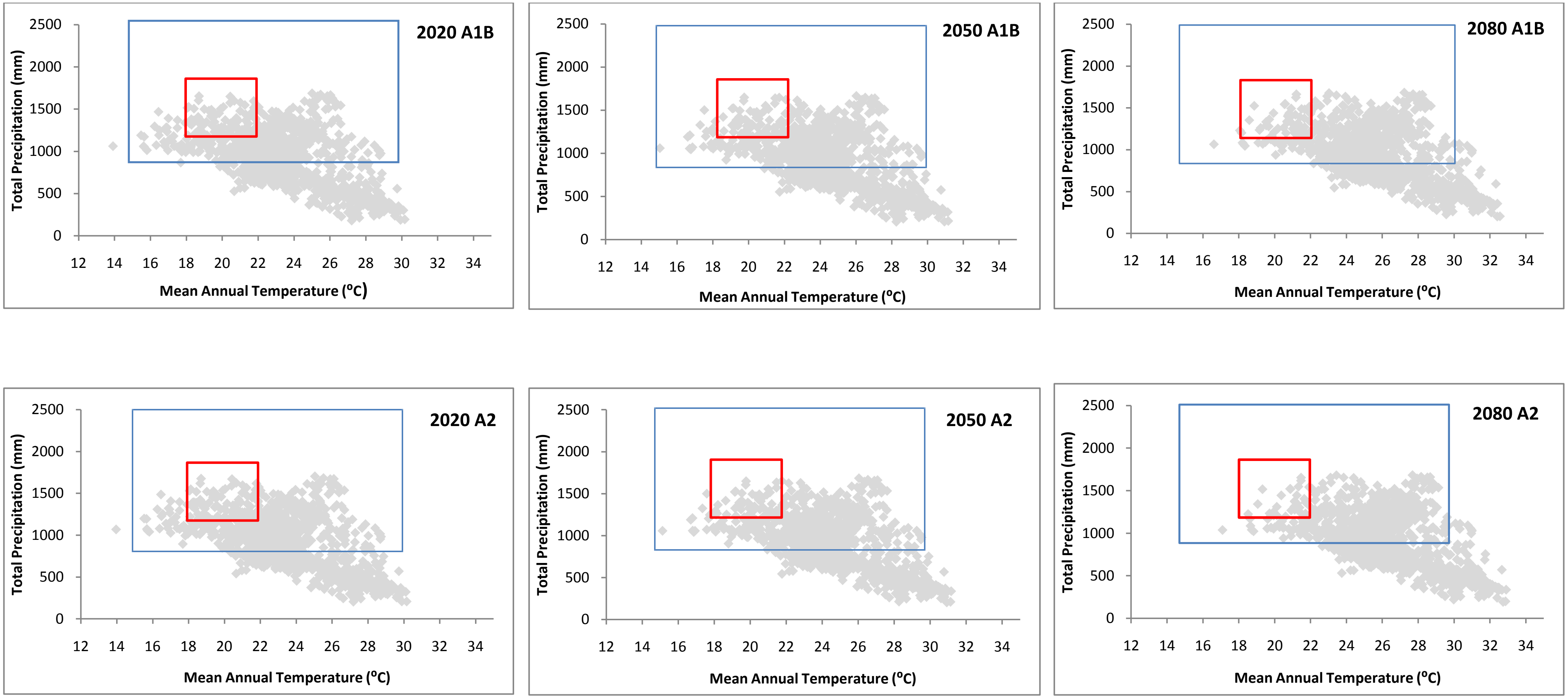


Figure 5.3: A 2D bioclimatic envelope of all land cells within East Africa, with the thresholds of optimal (red) and tolerable (blue) climatic thresholds for *C. arabica*. Climatic data is based upon the mean results from three different GCMs, and under the A1B and A2 emissions scenario.

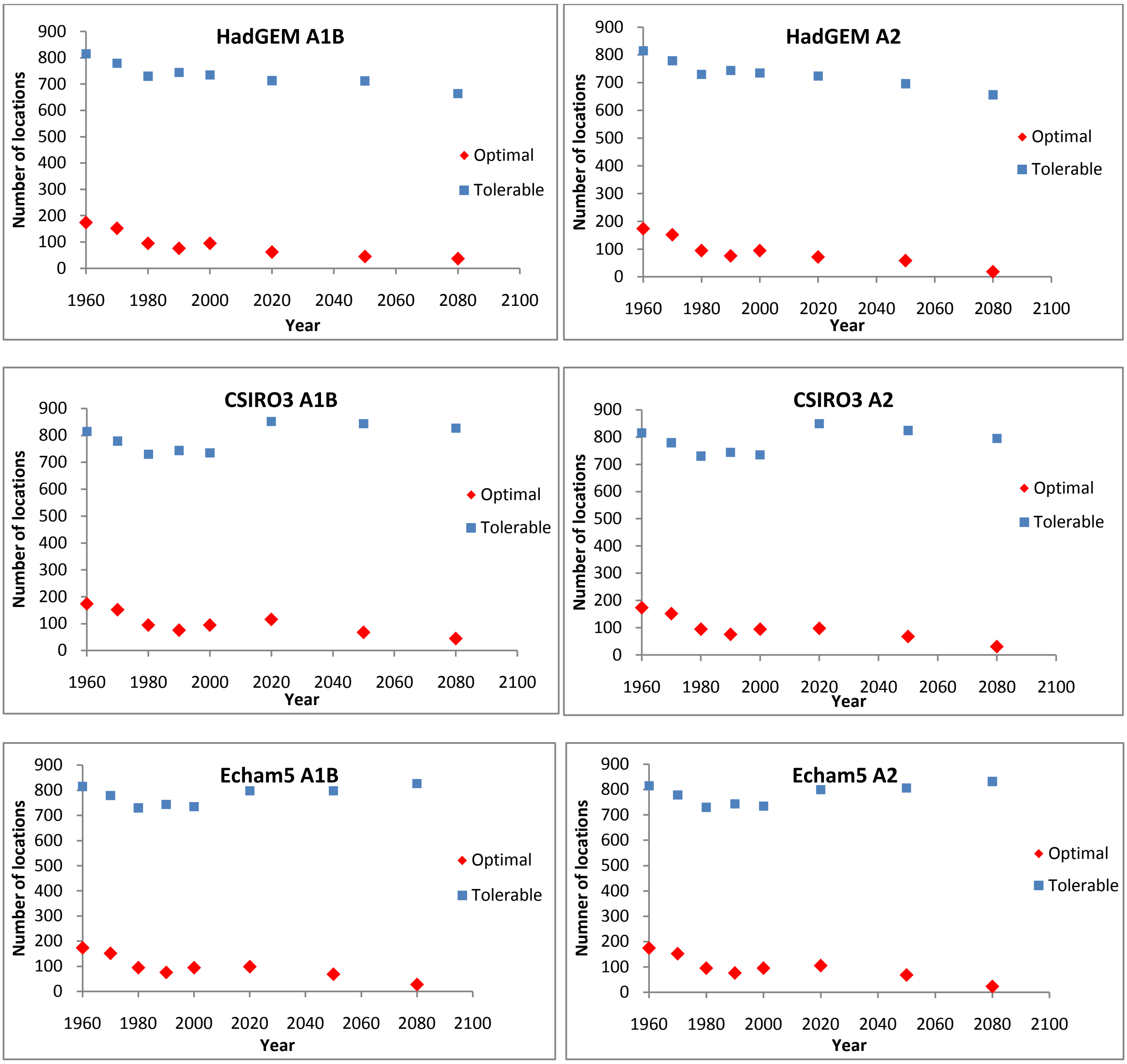


Figure 5.4: The number of suitable optimal and tolerable *C. arabica* growing locations in recent decadal time-slices and in 2020, 2050 and 2080, predicted by three GCMs under the A1B and A2 emission scenarios.

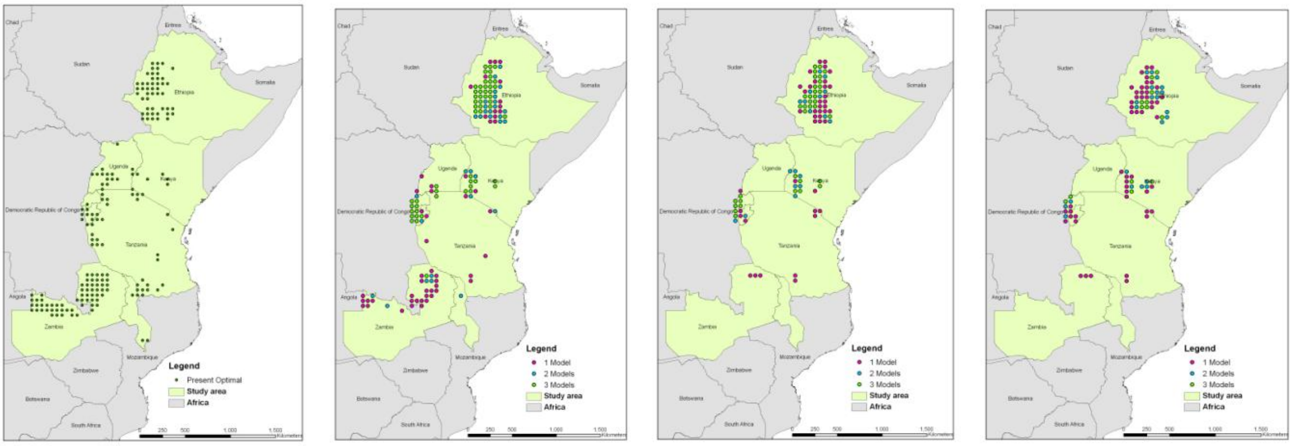
There is variation between the GCMs as to the number of optimal and tolerable locations identified as suitable for 2020, 2050 and 2080 (Fig. 5.5). Geographically it is seen that, in 2020, under the A1B scenario, areas of North and Northeast Zambia, and Southeast Tanzania are identified as being suitable by a single model. All three models consistently identify areas of West Ethiopia, Rwanda and Burundi as suitable. By 2050, all optimal locations in Zambia disappear, except three identified by one model, and there are no optimal locations in Uganda. The number of sites in Rwanda and Burundi decline (Fig. 5.5).

By 2080, in Ethiopia there is greater uncertainty, with only single models identifying areas as suitable, as opposed to two or three models in 2050. There is a decline in the number of suitable locations in West Ethiopia (Fig. 5.5). Between 2050 and 2080, there is no further decline in the number of optimal sites in East Africa, other than in Ethiopia, where there is a decline in both the number and certainty of optimal locations. Under the A2 emissions scenario, the pattern of distribution is similar to that of A1B, but there are fewer optimal sites in Zambia in 2020, and in 2050 the number of optimal sites in Ethiopia has declined further. The southern and northern tips of suitable areas in Ethiopia are indentified by a single model in 2050 under the A2 scenario (Fig. 5.5). The areas of suitability by 2080, under the A2 scenario are fewer than the A1B scenario, with no sites in Malawi, Uganda and Zambia, only four sites in Burundi and Rwanda, and very patchy distribution in Ethiopia (Fig. 5.5).

The number and distribution of tolerable locations stays more consistent than the number of optimal sites. In 2020, there are a large number of sites predicted as suitable by all three models, with the greatest uncertainty in southern Zambia (Fig. 5.5). By 2050, the number of tolerable locations declines in Zambia, and there is greater inconsistency between models for suitable locations in Northeast Tanzania. In 2080 there is greater inconsistency between models in Ethiopia, southern Zambia and Northeast Tanzania (Fig.5.5).

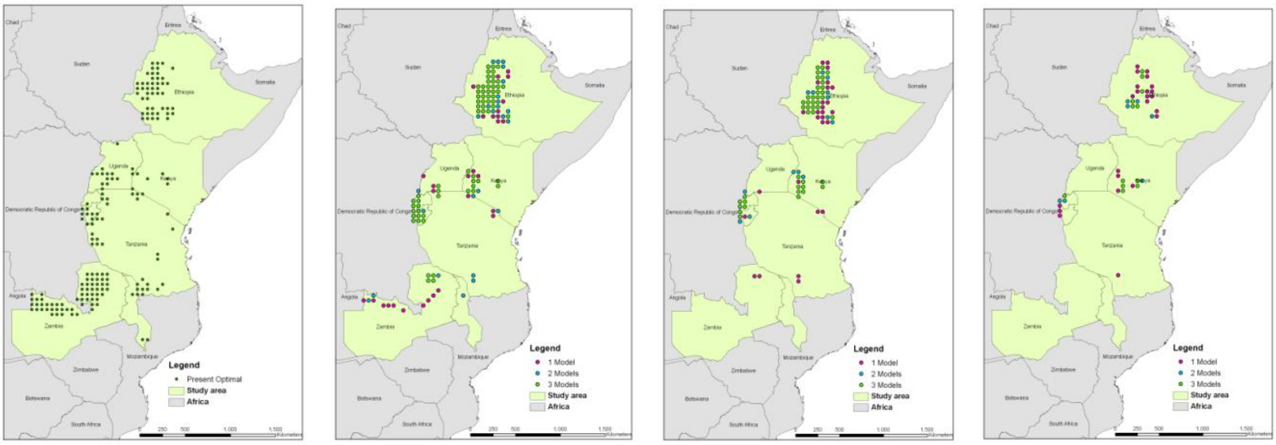
More optimal sites are lost under the A2 emissions scenario than the A1B scenario (Fig. 5.6). Malawi and Tanzania lose all suitable optimal locations in the future time periods studied, and Uganda and Zambia lose all optimal sites in 2050 and 2080 under the A1B emission scenario (Fig. 5.6). Under the A2 emission scenario, Uganda and Zambia retain 100% and 50% respectively of optimal locations in 2020, but this declines to 0% by 2080. Rwanda retains a higher percentage of optimal locations, and in 2020 under both scenarios 100% of present day sites remain suitable.

a) Optimal Locations: A1B scenario



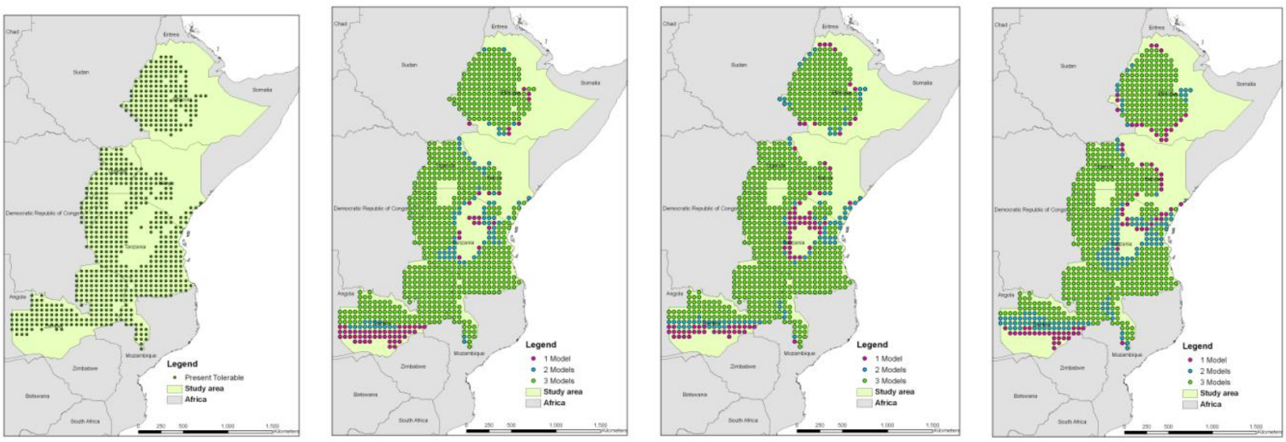
Present n= 76 2020 n= 138 2050 n=94 2080 n=85

A2 scenario



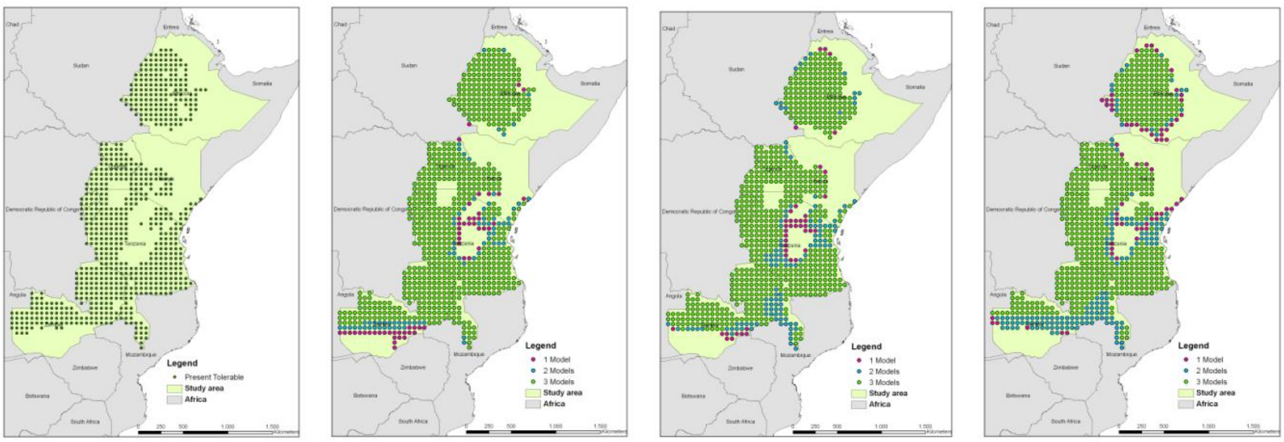
Present n= 76 2020 n=120 2050 n= 83 2080 n=42

b) Tolerable Locations: A1B scenario



Present n= 744 2020 n= 860 2050 n= 869 2080 n= 871

A2 scenario



Present n= 744 2020 n= 852 2050 n= 843 2080 n= 857

Figure 5.5: The geographical distribution of climatically suitable locations for *C. arabica* in 2020, 2050 and 2080 (Pink= location predicted as suitable by one model, Blue= location predicated as suitable by two models and Green=location predicted as suitable by three models)

In 2050 under the A1B scenario 100% of locations are still suitable, but under the A2 scenario this drop to 50%. In 2080 under both emission scenarios, 50% of the present day suitable sites remain (Fig. 5.6).

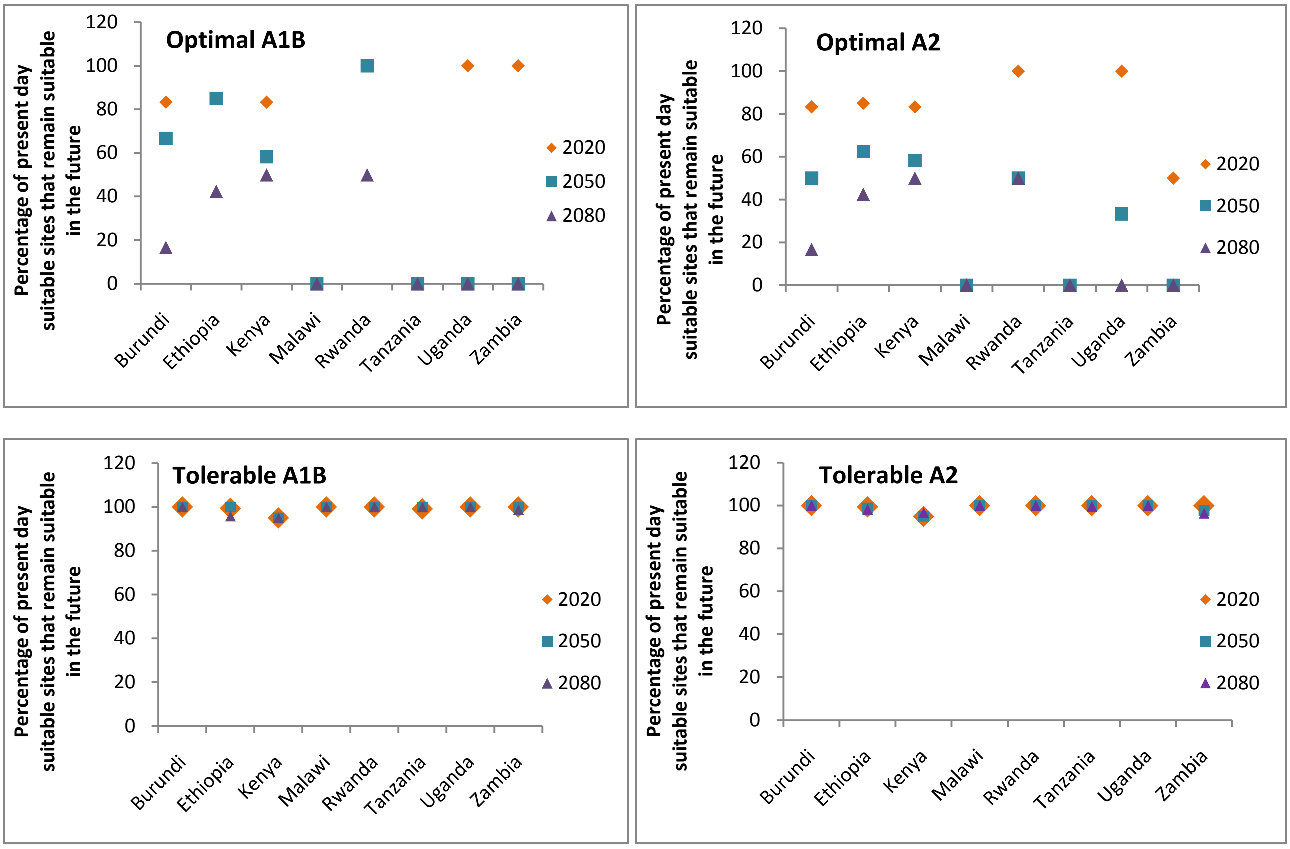


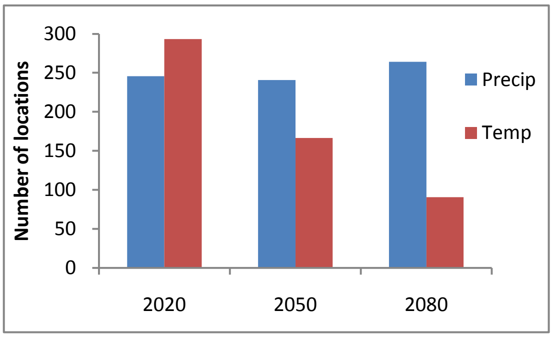
Figure 5.6: The percentage of current suitable *C. arabica* growing locations by country, which remain suitable in the future, calculated from the combined results of three GCMs.

In Burundi, around 80% of the present day optimal sites are retained in 2020 under both scenarios, but this declines to 66.6% and 50% by 2050 under the A1B and A2 scenarios. In 2080, there is a further drop to 16.7% under both scenarios. Around 85% of present day suitable optimal locations are retained in Ethiopia in 2020 and 2050, under the A1B scenario, but this reduces to 42.5% by 2080. The A2 scenario shows similar results, except for 2050 when 62.5% of present day locations remain suitable. Results for Kenya are similar under both emissions scenarios, with a gradual decline in the number of optimal locations that remain suitable, from 83.3% in 2020 to 50% in 2080 (Fig 5.6). The largest change in the number of optimal locations occurs after 2050.

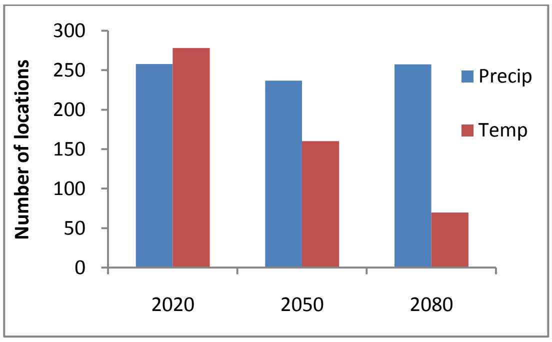
The number of tolerable sites that remain suitable in the future remains at 100% for all countries except Kenya, Tanzania and Zambia in 2050 and 2080, where declines of up to 5% are predicted. Across the whole East African region, there is rise of up to 10% from the present day in the number of tolerable locations by 2080 under the A1B and A2 emission scenarios (Fig. 5.5).

The role of temperature and precipitation as limiting factors to coffee growth changes through time. The affect of these climatic functions on optimal and tolerable thresholds also varies. In 2020, there are more locations that have optimal mean temperatures than optimal total precipitation, suggesting that precipitation is the limiting factor to the number of optimal coffee growing locations. By 2050 and 2080 this trend has reversed, and more locations have optimal precipitation than optimal temperature. In 2080 under both the A1B and A2 emissions scenarios, there are approximately 260 locations across the East African region studied which have optimal annual precipitation totals, but only 70 that have optimal mean annual temperatures (Fig. 5.7). This suggests that temperature is the limiting factor in the number of locations considered optimal for arabica coffee.

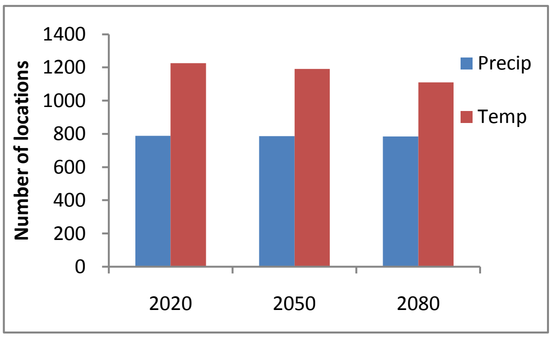
When tolerable climatic thresholds are considered, there are approximately 780 with suitable annual precipitation, under both the A1B and A2 emissions scenarios across all time periods. In comparison, the number sites with tolerable mean annual temperatures is between 1100 and 1200, depending upon the emissions scenario used (Fig. 5.7), indicating that precipitation is the more limiting factor than temperature in the number of tolerable sites.



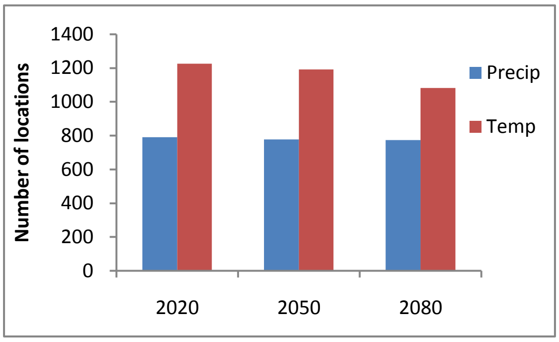
a) Optimal A1B scenario



b) Optimal A2 scenario



c) Tolerable A1B scenario



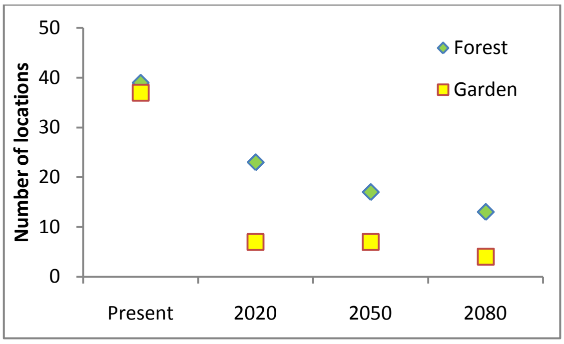
d) Tolerable A2 scenario

Figure 5.7: The number of coffee growing locations identified as suitable, under optimal and tolerable temperature and precipitation thresholds, through time. Mean temperatures and precipitation as predicted by three GCMs, were used to represent the future climate.

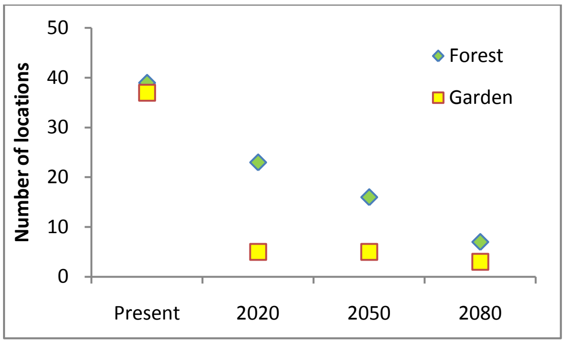
5.3.3. Future climatic suitability of garden and forest coffee in Ethiopia

In Ethiopia, it is predicted that there will be a large decline in the number of climatically optimal forest and garden coffee growing locations through time (Fig. 5.8 a & b). The prediction for 2080 under the A2 emissions scenario suggests that the number of forest coffee sites could be just seven, a loss of 82% from the present day (Fig. 5.8). It is expected that the number of current garden coffee sites, still suitable in 2080 under optimal conditions, is four and three for the A1B and A2 emissions scenarios respectively. Generally the A2 emissions scenario results in a lower number of suitable locations.

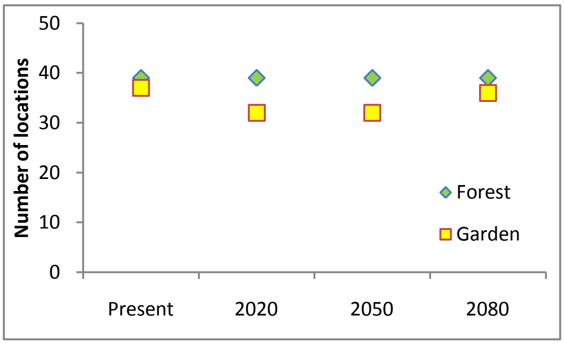
When tolerable climatic limits are considered, 100% of current forest coffee growing sites will remain suitable across the time period studied (Fig 5.8). The number of garden coffee locations declines by 14% by 2020 in comparison to the present day, but the number increases to present day values again in 2080.



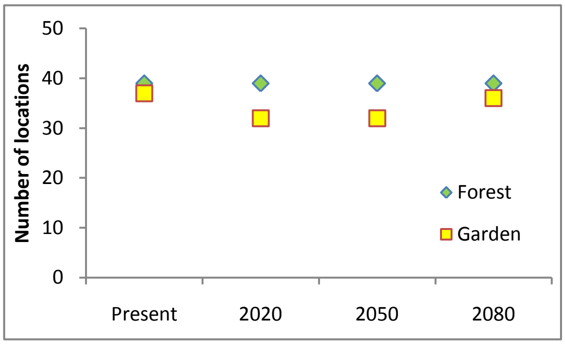
a) Optimal A1B scenario



b) Optimal A2 scenario



c) Tolerable A1B scenario



d) Tolerable A2 scenario

Figure 5.8: The number of forest and garden coffee growing locations in Ethiopia under optimal and tolerable climatic conditions through time. Climatic conditions are calculated as a mean of the output from three GCMs.

5.4 Discussion

5.4.1 The impact of changing climatic trends on arabica coffee production

Arabica coffee is highly sensitive to temperatures above 30°C as exposure to these warm temperatures even for short periods of a few hours can cause considerable harm and damage to photosynthetic pathways (Franco, 1958, cited from: DaMatta 2004; Descroix and Snoeck, 2004; Eakin *et al*., 2009). Future mean monthly temperatures in East Africa could be as high as 28°C in 2080 (Fig. 5.2d), and this would have severe consequences for the productivity, and quality of coffee produced, because is far higher than the optimal night time temperature of 18°C and day time optimal of 22°C (Descroix and Snoeck, 2004). Temperature is critical to a plants rate of development and can affect specific stages of a plants annual life, such as flowering (Craufurd and Wheeler, 2009). Changes in developmental stages can reduce productivity and yields.

Apart from the predictions of the HadGEM model, total annual precipitation does not decline greatly (Fig.5.1a), and it has been shown that temperature is likely to be the limiting climatic factor in the number of optimal arabica coffee locations in East Africa over the next century (Fig. 5.6). Other studies of crop plants in the region have shown temperature to be the limiting factor to productivity (Schlenker and Lobell, 2010), and similarly in Veracruz, Mexico, temperature limited the potential distribution of arabica coffee (Gay *et al*., 2006).

Coffee is sensitive to the seasonal distribution of rainfall, and these monthly patterns of precipitation are predicted to change (Fig. 5.1b-d). Arabica coffee requires a 12 - 14 week dry period before flowering and this is essential for higher yields (Alvium, 1960; Cannell, 1985; Crisosto, 1991; Cambrony, 1992; Gay *et al*., 2006). If rainfall is continuous throughout the year with no prolonged dry period, arabica coffee flowers at intervals throughout the year, resulting in a patchy harvest and poor yields in terms of both quantity and quality (DaMatta, 2004). Many of the GCMs show a reduction in the length of the dry season with precipitation rising through July and August. By 2080, August precipitation could be 50% higher than the present day (Fig. 5.1d), which could affect the quality and quantity of the yield. Other studies have noted that a limitation to investigations has been the inability to include monthly or seasonal variation in future predictions of species distribution or yield forecasts (Bakker *et al*., 2005).

There are a number of other factors that the model does not consider. For example, in Tanzania as temperature rises, melt water from glaciers on Mt Kilimanjaro will initially increase water availability for irrigation. Over time, as glaciers retreat and melt, this will decline and water shortages are expected to emerge in parts of Tanzania once served by the annual surges of melt water (Soini. 2005). This will affect water availability, so despite no large decline in precipitation over the coming century (Fig. 5.1), actual water availability may be far less than the present day.

There are a large number of interactions between mean annual temperature and total precipitation which are not modelled or accounted for in this study. Seasonal variables in temperature and precipitation were unable to explain much of the variation in past yields (Table 4.4), so it is only possible to infer the possible effects of future climatic changes on arabica coffee production.

5.4.2 Changes in the number of optimal and tolerable arabica coffee growing locations in East Africa

The number of locations potentially tolerable for *C. arabica* across East Africa rises over the next century, as mean annual temperatures rise (Fig. 5.4 and Fig. 5.5). Almost all of the present day tolerable locations remain suitable over the time period studied, and new locations emerge, because the total number of tolerable locations increases during the next century. These new locations are not predicted to be concentrated in a single area (Fig. 5.6). Although the number of tolerable locations is predicted to increase, climatic changes within a grid cell may still negatively affect productivity and yield. Atmospheric composition affects the growth, development, and productivity of plants, and although increased CO_2 will increase arabica coffee yields, higher ozone will negatively affect plant production (Parry *et al*., 2004; Challinor, 2009; Gregory *et al*., 2009). Soil conditions, presence of pests and diseases, and socio-economic factors will change under future climatic changes, and may negatively affect arabica coffee production (Willson, 1985; Jaramillio *et al*., 2009).

The number of suitable optimal locations declines across the next century with less than 15 potential optimal locations by 2080 (Fig. 5.4 and Fig. 5.5). Up to 100% of present day optimal locations are predicted to be lost in a number of countries, including Malawi, Tanzania, Uganda and Zambia (Fig. 5.6). This magnitude of potential loss in climatically suitable areas is not uncommon; some European plants are predicted to lose up to 80% of their range by 2080 under the A1 emissions scenario (Thuiller at al., 2005).

Previous studies have shown that current arabica coffee growing locations are expected to decline in suitability under future climatic changes. In 2002, it was predicted that there would be a 'dramatic reduction' in the total area suitable for coffee growing in Uganda if temperatures rose 2°C from present day levels (GRDI, 2002). The areas suitable for arabica coffee in Brazil are predicted to decline by up to 95% in three states and by up to 75% in a fourth state, if temperatures rise by 5.8°C (Cerri *et al*., 2007). In Kenya it is expected that, by 2020, there will be a general decrease in the area suitable for arabica coffee and, by 2050, a 50% decline in suitable areas is expected in the majority of regions. Only areas in the Rift Valley will become increasingly suitable for arabica coffee (Eitzinger *et al*., 2010). These results support this study's findings that the number of present day arabica coffee locations fall by at least 50% in all countries by 2080 under both the A1B and A2 emission scenarios (Fig. 5.6).

'Adaptation to climate change for smallholders of tea and coffee' (AdapCC) was a collaborative project between the fairtrade coffee company, Cafédirect and the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. Between April 2007 and February 2010, AdapCC conducted several case studies with smallholder tea and coffee producers in Kenya, Uganda, Tanzania, Mexico, Peru and Nicaragua to develop strategies to cope with the risks and impacts of climatic change (AdapCC). Results from analyses conducted by the AdapCC project team concluded that in current coffee growing regions of Peru, Nicaragua and Mexico, areas of suitability could decline by up to 50% by 2050. A small number of new locations will become suitable for arabica coffee cultivation and, generally, areas at higher altitudes will become more suited to coffee growing as temperatures are cooler (AdapCC, 2009). This study supports the AdapCC findings, and showed that a small number of new sites will become suitable for arabica coffee growing in 2050 and 2080 under tolerable climatic conditions (Fig. 5.5).

In a study of the future suitability of arabica coffee in Veracruz, Mexico, Gay *et al*., (2006) conclude that future changes in precipitation and temperature could cause a reduction of up to 34% in coffee production by 2020. The study suggests that temperature is the most relevant climatic factor (Gay *et al*., 2006). This study of arabica coffee in East Africa shows that until 2020 precipitation is the limiting factor in the number of optimal coffee growing locations. In 2050, and 2080, temperature becomes the limiting factor and reduces the number of optimal locations (Fig. 5.7). Precipitation is the limiting factor in the number of tolerable sites for arabica coffee throughout the whole region, for the future time periods studied.

Changing species distributions over the coming century, due to climatic changes, are widely predicted in both animal and plant species. In a study predicting future extinction risks, 15%-37% of species in the study regions (Mexico, Queensland and South Africa), risk becoming extinct by 2050. Species included in the study included mammals, birds, reptiles, butterflies and plants (Thomas *et al*., 2004). Up to 51% of land in the Indo-Gangetic Plains in India are expected to become unsuitable for wheat production due to climatic changes by 2050 (Ortiz *et al*., 2008), and a study of the broad headed snake in Australia suggests that 46% of known, present day locations will become unsuitable by 2070 (Penman *et al*., 2010). The decline in suitability of land under future climatic changes is a recognised challenge, and our findings that the number of optimal locations for arabica coffee will decline over the 21st century are supported by studies in other geographic regions.

5.4.3 The future of garden and forest arabica coffee in Ethiopia

In Ethiopia, 20% of present day coffee locations will become unsuitable by 2050, and this rises to 60% of locations in 2080 (Fig. 5.5). Much of this decline is within the forest coffee region of Southwest Ethiopia. By 2080, less than 15 forest coffee sites remain optimal across Ethiopia, a decline of 82% (Fig. 5.8). The loss of forest coffee growing sites is of global significance and importance, as the coffee forests regions of Ethiopia are the most genetically diverse source of arabica coffee in the world (Senbeta *et al*., 2007; Labouisse *et al*., 2008; Schmitt *et al*., 2009). In the future, new breeds and cultivars of coffee are likely to hold the key to ensuring that arabica coffee can withstand climatic changes, and new cultivars might be required to maintain commercial cultivation in some parts of the world. The coffee forests of Ethiopia are a rich resource of genetic diversity, and the loss of these sites is a cause for concern. Large numbers of families are dependent upon the coffee forests for their livelihoods, and the loss of their productivity is likely to cause severe economic consequences (Schmitt *et al*., 2009). As forest coffee, is by nature, wild and almost unmanaged in many areas, mitigating and adapting to climate change will be challenging.

The decline of arabica coffee forests however is difficult to predict as many factors influence their existence. Coffee is an understorey species, and future investigations should examine the likely impacts of climatic change on the primary forest trees. Climatic change is expected to result in a change of forest type and species (Bezabih *et al*., 2010). Depending upon the resilience of the forest trees to climatic change, the impact on arabica coffee may be less than expected, or more if the forest stand is expected change significantly, as climate changes. Forests can provide a more sheltered environment and more protective atmosphere than field grown crops, and forests may provide a greater resilience to climatic change through changed water holding dynamics, interception of heavy rainfall, and shaded environments (Senbeta *et al*., 2007).

Further pressure on the coffee forests of Ethiopia is likely to come from deforestation through land-use pressure as population increases, or economic pressures as timber products are high in value and can bring in much needed money to areas of Ethiopia (Petit, 2007; Schmitt *et al*., 2009). The numbers of garden coffee locations in Ethiopia are predicted to decline according to this study (Fig. 5.6). Garden coffee is presently at the bioclimatic limit of suitability so it could be expected that as temperatures rise further, fewer areas will remain suitable for arabica coffee cultivation in the future (Fig. 3.9).

5.4.4 Limitations

Using mean annual temperatures and total annual precipitation as predictors of climatic suitability has limitations. Crops do not respond directly to the amount of precipitation but, instead, to water availability. Evapotranspiration, soil water capacity and management systems affect water availability, along with other factors that are not modelled or accounted for in this study. While precipitation may act as a good proxy for water availability, especially in large parts of East Africa where arabica coffee is most often farmed as a rain-fed crop, this study takes no account of atmospheric humidity or diurnal temperature changes, that can produce heavy morning dews, in assessing the water-availability for arabica coffee (Willson, 1985).

Mean annual temperature and precipitation are not the only variables that will affect the distribution and success of arabica coffee. Atmospheric composition affects yields and plant health and some studies suggest that yields of C_3 plants such as rice, wheat and soybean could rise by 10% - 20% under increased CO_2 concentrations (Slingo *et* *al*., 2005; Schmidhuber and Tubiello, 2007). Arabica coffee is a C_3 plant and should benefit from yield increases through increased CO_2 atmospheric concentrations.

Arabica coffee requires slightly acidic soils and a good supply of nutrients, especially potassium (Willson, 1985). Nutrient availability may be affected by future climatic change, through changing interactions between minerals, water supply and above-ground versus below-ground processes (Montoya and Raffaelli, 2010). Gregory *et al*. (2009), concluded that the number of soil dwelling weevil larvae *Sitonia spp,* which attacks legume root nodules, will increase under higher CO_2 concentrations, reducing the rate of nitrogen fixation (Gregory *et al*., 2009). Soil quality and nutrient availability was not considered in our assessment of potential suitability of future locations.

Arabica coffee is susceptible to a number of pests and diseases. The coffee berry borer, *Hypothenemus hampei,* is the most devastating pest of coffee in the world, and as mean annual temperatures increase across East Africa (Fig. 5.2) the incidence of *H. hampei* will increase, as the insect develops fastest at temperatures between 27°C - 30°C (Jaramillo *et al*., 2009). It is estimated that for regions with mean daily temperatures of less than 26.7°C, each 1°C rise in temperature increases the rate of infection by 8.5% (Jaramillo *et al*., 2009). Currently, mean temperatures across East Africa are around 22°C but this will increase to 26°C by 2080 (Fig. 5.2). Before 1984, the region of Jimma, Southwest Ethiopia was too cold for *H. hampei* to develop; today there are at least one-two cycles of generation each year (Jaramillo *et al*., 2009). Coffee Berry Disease, *Cooletotrichum coffeanum*, attacks young coffee berries and thrives in wet conditions as rainfall is required for spore production and dispersal (Waller, 1985). The future climate in East Africa may become more favourable for a variety of pests and diseases, decreasing the productivity of arabica coffee.

Disease may burden the local population, as malaria is predicted to expand into new areas within East Africa and water-borne sanitation diseases such as cholera thrive in warm water environments (Hay *et al*., 2002; Lipp *et al*., 2002). As East Africa becomes warmer and wetter (Fig.5.1 and Fig. 5.2), new environmental conditions may favour the development of human diseases. Increasing illness and mortality amongst the populations of East Africa limits the workforce available to manage farmland. Coffee is a labour intensive crop, requiring pruning on a regular basis to maintain the highest quality and quantity yields (Gay *et al*., 2006). Malnutrition and hunger is expected to remain high in large parts of East Africa, and some regions are expected to endure higher rates of malnutrition than the present day (Liu *et al*., 2008).

There are a large number of abiotic factors that this study does not consider when predicting the areas of future suitability of arabica coffee. Such factors may negatively affect the number of suitable arabica coffee locations. This study utilised mean annual temperatures and total precipitation as this data was widely available. Data on other variables were less widely available.

5.5 Conclusion

Over the next century, it is predicted that mean annual temperatures will rise, and total precipitation will fall (except the Echam5 model in 2080) across East Africa. Seasonal variations and rainfall patterns will change from the present day, with the dry season becoming shorter over the next century, and rainfall becoming more evenly distributed throughout the year. Seasonal mean temperatures are predicted to rise to 28°C during the hottest months under the A2 emissions scenario. These climatic combinations are likely to decrease arabica productivity and yield quality.

The number of potential tolerable arabica coffee growing locations is expected to increase over the next century and only a few present day tolerable locations will become unsuitable. Potential optimal growing locations decline by 30% under the A2 emissions scenario by 2080, after an initial increase in the number of optimal location, above the present day values, in 2020 and 2050. Under the A1B emissions scenario the number of potential optimal locations increases by 50% from the present day by 2020. The number of optimal locations is then predicted to decline, but still stay above the number of present day optimal locations. In 2080, it is expected that there will 10% more optimal locations than the present day.

There is a change in the geographical distribution of potential optimal sites and in Malawi, Tanzania, Uganda and Zambia all present day optimal locations are unsuitable by 2080. Over 50% of present day optimal locations are unsuitable for arabica coffee production in each country studied by 2080. Under the A1B emissions scenario new optimal locations emerge across East Africa.

In Ethiopia, the number of present day forest and garden coffee locations that remain suitable under future climatic changes declines. In 2080, under the A2 emissions scenario, only three garden coffee and seven forest coffee locations will have optimal climatic conditions. This is of great concern as 15 million people are dependent upon the coffee industry in Ethiopia (Labouisse *et al*., 2008) and wild forest coffee has a rich gene pool.

Coffee farmers across East Africa will be affected by future climatic changes and in many present day coffee areas, production will be negatively affected due to increasing temperatures. Whilst some areas will become completely unsuitable for arabica coffee production, other regions will become less suitable and more marginal areas. Through careful management practices and adaptation some of the climatic changes may be mitigated and production less effected than it otherwise might be. Management and adaptations options are discussed in the next chapter.

Chapter 6

General Discussion

6.1 The effects of climatic changes on arabica coffee productivity in East Africa

6.1.1 Past and future climatic changes in East Africa

The climate of East Africa has become warmer, and according to this study, drier over the past 40 years, and this is shown through analysing trends in mean annual temperatures and total precipitation (presented in Appendix One, summary Table 3.1). Similar trends in warming have been identified in previous studies, and the rate of warming has increased since 1980 (Boko *et al*., 2007). The six warmest years of the 20th century, all occurred post 1987 (Hulme *et al*., 2001). Analysis of the trends in precipitation suggest a decline of -3.65mm each year (-0.03% of the average total annual precipitation) (Table 3.1), while other studies have concluded relative stability in the East African precipitation regime, and perhaps a trend of long-term wetting over the 20th century (Hulme *et al*., 2001). Hulme *et al*. (2001) conclude that 1961, 1963 and 1997 were particularly wet years, and this study supports these findings, as all have total precipitation above the period mean. The recording of climatic information in East Africa has historically been more challenging, as the total number of recording stations is less, and the spatial distance between stations greater than in many areas of the world (New *et al*., 2000). Discrepancies between different datasets can be expected, as some precipitation values are dependent upon a parameterization processes (which stimulate systems such as cloud cover, evapotranspiration processes, and topography), to determine precipitation in regions where monitoring is conducted at large spatial scales.

Climatic change over the next century will result in warmer mean annual temperatures across East Africa (Boko *et al*., 2007). Predicted mean temperatures, from three global circulation models used in this study support these findings, and suggest that some regions of East Africa could be up to 4°C warmer than the present day by 2080, an increase of nearly 20% (Fig. 5.2). Trends in future precipitation are less certain; the IPCC, (2007), suggests that precipitation will increase, but Funk *et al*. (2008) questioned the ability of global circulation models to capture and simulate the effects of the warming of the Indian Ocean, which affects precipitation regimes in East Africa. The HadGEM model used in this study, predicts a decline of nearly 150mm from the present day (approximately 15%) in 2020, 2050 and 2080 (Fig. 5.1). The CSIRO3 and Echam5 models predict a decline of up to 75mm of precipitation from the present day in 2020 and 2050, (and 2080 for the CSIRO3 model), but the Echam5 models suggests a similar, or 20mm increase from the present day level of precipitation (dependent upon the emission scenario used) in 2080 (Fig. 5.1). Despite the uncertainty in overall trends in precipitation over the next 100 years, it is expected that storm activity will be greater than the present day and that the frequency of high-intensity rainfall events will increase (Easterling *et al*., 2000; Boko *et al*., 2007).

6.1.2 Climatic change and the suitability of arabica coffee in East Africa

Tolerable and optimal climatic thresholds for arabica coffee growth, based upon mean annual temperature, and total precipitation were identified from previous studies (Fig. 3.1). Climatic factors affect the distribution of a species, and changes in climate can affect the suitability of a region, to a particular species (Walther *et al*., 2002). For example, eleven out of 46 southerly butterfly species in the United Kingdom have expanded their range in a northerly direction over the past 20 years, and this can be attributed to climatic warming (Hill *et al*., 2002).

Using the optimal and tolerable climatic thresholds, the number and location of climatically suitable coffee growing locations were identified throughout East Africa (Fig. 3.6 & Fig. 3.7). A declining trend in the number of both optimal and tolerable climatically suitable locations has been observed over the past 40 years (Fig. 3.5 and Table 3.1). Based upon the average of 1990-99 mean annual temperatures, over 50% of locations in East Africa have mean annual temperatures above the upper optimal threshold of 22°C (Fig. 3.3). The trend in warming temperatures over the same time period in East Africa, suggests that warmer mean annual temperatures have negatively affected the number of suitable coffee growing locations. Other studies have previously attributed the rise of global mean temperatures during the 20th century to declines in suitability, and shifts in range of species (Parmesan, *et al*., 1999; Rosenzweig *et al*., 2008).

Previous studies have shown that under climatic change, and particularly global warming, species tend to shifts pole-wards (Parmesan *et al*., 1999; Hill *et al.*, 2002). In a study of 1700 different species, Parmesan *et al*. (2003) showed that during the 20th century, the range of species shifted 6.1km per decade pole-wards (or metres per decade upwards). Despite trends for pole-ward migration, few new areas of climatic suitability for arabica coffee have occurred in East Africa over the past 40 years (Fig. 3.7). This suggests, and is confirmed by considering present-day actual distribution of arabica coffee in Ethiopia, that the tolerable and optimal bioclimatic envelopes of coffee, are already at the limits of the East African climate-space (Fig. 3.3 and Fig.

3.9). A study of arabica coffee distribution in Mexico, supports this conclusion, and suggests that coffee in the region is already grown in areas that are too warm, and this affects productivity (Gay *et al*., 2006).

The bioclimatic envelope of actual coffee growing locations in Ethiopia, suggests that arabica coffee is being cultivated successfully in areas with climatic conditions outside of the tolerable climatic threshold identified in this study (Fig. 3.9 & Table 3.3). Garden coffee is found in areas of Ethiopia with mean monthly temperatures as high as 31.2°C, and with total annual precipitation as little as 721.2mm (Table 3.3). Some forest coffee areas (which are unmanaged) are found in regions with monthly mean temperatures up to 27.2°C. This suggests that coffee can be managed to ensure that productivity continues outside of the optimal and tolerable climatic thresholds. As temperatures are predicted to increase in East Africa over the next century, and the pattern of precipitation becomes increasingly uncertain, management and adaption strategies need to be considered to ensure the future of agricultural productivity.

6.2 Adaption and resilience to future climatic changes in East Africa

6.2.1 Farmers perceptions of climatic vulnerability

The successful production of arabica coffee in East Africa is dependent upon favourable climatic conditions, world coffee prices, availability of the work force, land availability and many more socio-economic factors (Gay *et al*., 2006; Eakin *et al*., 2009). Although all of these variables affect yields and production of *C. arabica,* climate is considered to be one of the most influential factors in successful production (Gay *et al*., 2006). Results from a range of GCMs suggest that mean annual temperatures and total precipitation in East Africa countries will change over the next 100 years (Fig. 5.1 & 5.2; Mertz *et al*., 2009). Communicating these changes and their potential effects to farmers is complex (Boulanger *et al*., 2010).

Smallholder farmers are very aware of climatic changes and the impact these have on yields and successful production. Many farmers associate droughts and periods of prolonged heat stress with poor yields and food insecurity (Mertz *et al*., 2009; Tucker *et al*., 2010). Despite this awareness of climate, most farmers do not perceive climatic change to be the biggest risk to their livelihoods and success; for example, economic factors, world coffee price, and illnesses were ranked as more significant risks by farmers, interviewed in a number of studies in Central America and Africa (Mertz *et al*., 2009; Tucker *et al*., 2010). Coffee farmers questioned in Mexico perceived risks posed by climatic changes as irrelevant compared to economic and market threats (Eakin *et al*., 2005). Awareness of long-term, future climatic trends are low, and one of the first challenges in implementing adaption strategies in East Africa is to raise awareness of climatic impacts and the potential risk for arabica coffee farmers.

6.2.2 Adaptation strategies for arabica coffee farmers

The potential negative impacts of future climatic change on agricultural productivity are well documented (Parry *et al*., 2004; Slingo *et al*., 2005; Jones and Thornton, 2009). For staple food crops, including wheat, maize and rice, adaptation strategies include, earlier sowing dates, changing cultivars to those more tolerant of heat or water stress, diversification of crops to include an early season maize harvest followed by a crop of beans, and varying cropping density to aid water management (Howdon *et al*., 2007; Dinar *et al*., 2008; Lhomme *et al*., 2009; Jones and Thornton, 2009; Thornton *et al*., 2010). Coffee management and adaption is more complex, because *C. arabica* is a perennial crop, taking three years to mature and frequently economically viable for ten years or more (Teketay, 1999; Tucker *et al*., 2010). In areas of Tanzania, included in this study, some coffee trees were planted more than 50 years ago (Baffes, 2005).

Coffee farmers make long-term investment decisions and cannot modify the crop cycle as climatic patterns change. Arabica coffee farmers will rarely make the decision to change crops and to cease cultivating coffee, as this requires an input of labour and money to cut down the trees (Gay *et al*., 2006). It is a permanent decision that farmers who were studied in Mexico were unwilling to make, as they believed that future price rises would make coffee production economical in the future, and they wished to preserve the tradition and culture of coffee growing (Gay *et al*., 2006). Converting land to other uses can severely impact the surrounding ecosystems, through surface run-off, soil erosion, nutrient availability and pest and disease dynamics (Soini, 2005; Eakin *et al*., 2009).

However, arabica coffee farmers in East Africa and organisations who work with rural communities in the region, can make changes to their farming practices to increase the likelihood of continued successful production. This study has shown that each country in East Africa will lose a different number of current arabica coffee locations (Fig. 5.6). Malawi and Tanzania lose all current optimal coffee growing locations by 2020 (Fig. 5.6), and only 25% of actual current garden coffee locations in Ethiopia remain optimal in 2020 (Fig. 5.8). The largest reduction in the number of future potential tolerable locations is predicted for Kenya (Fig. 5.6). Information such as this that assesses the risk posed by climatic change to different geographical areas can be used by pro-poor organisations (AdapCC, 2009; Thornton *et al*., 2010). Funding for adaptation is limited, and must be channelled to the regions which are most in need. This study has highlighted the regions that are likely to be most affected by future climatic changes and identified if it is temperature or precipitation that is the limiting factor in suitability. Future funding and investments should be directed towards these regions to build resilience in communities that will be most negatively affected.

6.2.3 Managing water availability and heat stress

The number of optimal arabica coffee growing locations in 2020 across East Africa will be limited by precipitation (Fig. 5.7), and although not explicitly shown, it is assumed that it is a lack of precipitation rather than too much precipitation that is the limiting factor. Rainfall is currently the limiting factors for arabica coffee development (Descroix and Snoeck, 2004). After 2020, temperature becomes the limiting factor in the number of optimal locations (Fig. 5.7), as precipitation begins to increase again towards present day levels under most GCMs (Fig. 5.1). This information suggests that water management is critical to the continued success of arabica coffee production in East Africa over the next ten years.

East Africa is heavily dependent upon rain-fed agriculture (Thornton *et al*., 2009; Schlenker and Lobell, 2010), and on-farm water management is critical. With a lack of finance and technical support, large-scale irrigation projects are rare (Dinar *et al*., 2008). Arabica coffee farmers can develop cheap, low input strategies to conserve water, and increase water use efficiency to overcome declining precipitation levels. Reducing soil evaporation by 25% and collecting 25% of surface run-off could increase global crop production by 19% (Rost *et al*., 2009). Mulching, a process during which leaf-matter and other organic material is left to cover the top layer of soil is a well utilised method to prevent soil water evaporation (Teketay, 2009). It is cheap and requires no technological input, making the technique well suited to East African coffee farmers.

Arabica coffee is a shade-tolerant plant and evolved as an under-storey species (Cannell, 1985). High yields and good quality coffee are produced by plants grown under shade (Lin, 2007). Careful planting of shade trees can increase the water available for arabica coffee plants, by cooling the air temperature and reducing wind speeds, decreasing evapotranspiration (Beer *et al*., 2008). Shade trees also limit soil erosion particularly during extreme events, such as heavy rainfall (Teketay, 1999). Increased planting of shade trees in arabica coffee farms may limit water loss and enable the continuation of arabica coffee cultivation in areas of Malawi, Tanzania and Ethiopia.

When investigating correlation coefficients it was found that JJA precipitation was the most highly correlated seasonal precipitation variable with arabica coffee yield in East Africa (Table 4.2). This coincides with the driest season in most of East Africa (Fig. 5.1). The need of a three month dry season for successful arabica coffee production has been discussed previously, and it is noted that future predictions from GCMs show a shorter dry-season than the present day (Fig. 5.1). In 2020, July and August levels of precipitation are higher than the present day and are the cause of the shortened dry period. To aid the successful cultivation of arabica coffee, surface water run-off should be harvested during these two months and stored on-farm to use as irrigation water in October and November, when future precipitation is expected to be less than the present day (Fig. 5.1). Arabica coffee requires water during these two months to initiate flowering (Cannell, 1985).

After 2020, the number of potential optimal growing locations for arabica coffee in East Africa is limited by temperature (Fig. 5.7). Studies of other crops and arabica coffee in Central America have concluded that high temperatures are the limiting factor in increasing crops yields and productivity (Gay *et al*., 2006; Schlenker and Lobell, 2010). Chapter 4 showed that JJA temperature was the most highly correlated seasonal temperature variable with yield (Table 4.2), although the warmest months are usually March and October (Fig. 5.2). A high correlation between JJA temperature and arabica coffee yield may have occurred due to the collinearality (shown through a significant correlation) between JJA temperatures and JJA precipitation (Appendix Two). As future JJA temperature rises (Fig. 5.2), evapotranspiration is likely to increase resulting in less water availability during the driest season of the year. This may not have any negative effects on coffee production because arabica coffee requires a dry period to stimulate floral initiation (Cannell, 1985).

A greater concern is perhaps the rise in March and October temperatures to a monthly average of 28ºC by 2080 (Fig. 5.2). This is far outside the optimal range of 18°C - 22ºC and will severely affect photosynthesis and fruit quality (Barros, 1997; Teketay, 1999; Descroix and Snoeck., 2004). The use of shade trees as an adaptation strategy is again viable to reduce the air temperature, and ensures that arabica coffee plants are shaded from direct insolation, limiting leaf damage (Franco, 1958; Eakin *et al*., 2009). Shade trees increase species diversity which increases biological and socio-economic resilience in the ecosystem (Fraser *et al*., 2006).

If investments are to be made into exploring new arabica coffee cultivars or breeding programmes are established, heat tolerant species should be sought. This study has shown that high temperatures are far more limiting than precipitation by 2080 for the number of optimal locations across the East African region (Fig. 5.7).

6.2.4 Options for diversification

Most arabica coffee in East Africa is farmed under low-input systems with little or no use of fertilizers or mechanisation (Dinar *et al*., 2008; AdapCC, 2009). The targeted use of some fertilizers could negate the decline in soil nutrients and minerals, increasing but not necessarily stabilising yields (Schlenker and Lobell, 2010). Most farmers cannot afford these chemicals and to adapt to these methods, an increase in general wealth would be required. Arabica coffee farming in East Africa is currently labour intensive, but poor management including inadequate use of mulching, no shade and not fully harvesting coffee berries leads to declining yields. Mechanisation and technical support could counteract these problems (Labouisse *et al*., 2008; Eakin *et al*., 2009).

In western markets the popularity and demand of specialist coffees has risen greatly over the last decade (Petit, 2007; Wiersum *et al*., 2008). This includes fairtrade, organic and premium varieties of arabica coffee. Farmers of these specialist products receive higher prices for their goods and it is a niche market, so they are less affected by the fluctuations in price when there are global surpluses of standard arabica coffee (Ghosray, 2010). Many arabica coffee farmers are able to diversify their income streams, for example by cultivating and growing other cash crops e.g. bananas, as shade trees (Teketay, 1999).

Much of the arabica coffee produced in Eastern Africa is naturally organic, as farmers cannot afford fertilizers and pesticides (Petit, 2007). However, organic certification is relatively expensive and involves a high level of paperwork to prove traceability. This is not accessible to the vast majority of arabica coffee smallholders in East Africa.

Forest coffee can also be certified and sold as a premium product but again this is not accessible for many farmers (Petit, 2007; Wiersum *et al*., 2008).

This study has shown that much of the land in Ethiopia that is currently used for garden and forest coffee will become unsuitable in the future, at least under optimal conditions (Fig. 5.8). Land might become more suitable for other crops, and farmers could decide to no longer cultivate arabica coffee. This would result in a rapid decline in the available gene pool of arabica coffee, as forest coffee in Ethiopia has the largest genetic diversity (Labouisse *et al*., 2007; Gole *et al*., 2008). Changes in land-use from forest to open crop land could cause severe land-degradation, increasing soil erosion and water and mineral losses.

6.3 Limitations and uncertainties in predicting the future suitability of arabica coffee in Eastern Africa

Limitations of the methods used to model and predict the potential suitability of arabica coffee over the next century have been discussed in previous chapters, but this section outlines some of the uncertainties and complications that exist, and that should be considered when examining the results of this study.

In modelling future areas that are climatically suitable for arabica coffee, only mean annual temperature and total precipitation have been considered. This is a relatively simple approach and does not capture the complexities and interactions between temperature and precipitation. An increase in winter temperatures in Veracruz, Mexico, reduced the availability of moist mist that once accumulated in coffee plantations during the cooler months (Eakin *et al*., 2009).

Only the physiological effects of climate on arabica coffee plants are considered; no modelling of future pest dynamics, availability of pollinators or the impact on soil as a result of a changed climate are included (Klein *et al*., 2003; Bakker *at al*., 2005). Extreme rainfall events can lead to leaching in soils, altering the pH and availability of nutrients (Senbeta *et al*., 2007). Crops do not respond linearly to climatic changes and thresholds will results in sudden declines of productivity and yield (Porter and Semenov, 2005).

Modelling potential sites for arabica coffee was done at a 0.5°×0.5° resolution, taking no account of the effects of local topography and land-use. East Africa has a poorer network of weather stations than many areas of the world and actual weather data for use in GCM models is interpolated to provide information for each 0.5°× 0.5° location (New *et al*., 2000; Schlenker and Lobell, 2010). High resolution climatic data and soil water holding capacity is unavailable for the region studied, but has provided detail and increased accuracy in other studies, such as modelling wheat in Europe (Bakker *et al*., 2005; Stehfest, 2007).

Modelling at a relatively high resolution and using future climatic variables as predicted by global circulation models, ignores the synergies between plants and local weather. Crop growth and development in a region throughout the year, can affect the local weather and climate, which in turn affects plant development (Pielke *et al*, 1998). Osborne *et al*. (2007) explore the use of coupled crop-climate models, which aim to capture the feedbacks between weather and crop growth and development. The use of such coupled models may provide more accurate information in the future as to the future distribution of arabica coffee.

Previous studies have shown that economic variables affect the production of coffee. Past data used to estimate yields and the area harvested may have been artificially high or low due the value of the global coffee market at the time. As prices rise, coffee farmers manage the crop more intensively producing higher yields independently of climatic variables (Schmitt *et al*., 2009). In Argentina, the progress and stability of the currency post-2001 sustained the development of the country's agricultural industry, increasing crop yields and productivity (Boulanger *et al*., 2010). When coffee prices declined between 1999 - 2004 coffee farmers abandoned plantations and switched to alternative crops, decreasing coffee production (Labouisse *et al*., 2008; Tucker *et al*., 2010). Whilst economic variables can affect arabica coffee production and yields, such factors do not affect the climatic potential of locations, and therefore the potential suitability of sites for *C. arabica* is as mapped in Fig. 5.5.

As the production of coffee is dependent upon a large number of factors (socio-economic, biotic and abiotic factors) it can be difficult to determine the cause and effect of variations, in particular with many of these variables being correlated (Bakker *et al*., 2005; Eakin *et al*., 2009). When describing global wheat yields, Hafner (2003) found that per capita gross domestic product and latitude could explain 50% of wheat yield variation. Other studies have shown that growing season length and temperature can explain similar levels of variation (Bakker *et al*., 2005), but for example GDP and growing season length may both act as proxy for soil quality.

The adaptive capacity of famers is not modelled, and detailed information on the ability of households in East Africa to adapt to climatic change is unknown (Thornton *et al*., 2010). Farmers have always adapted to climatic changes, through changing crop rotations and inputs and although this is likely to become more challenging farmers are resilient and will do what they can to avoid losing income (Jones and Thornton, 2008; Reidsma *et al*., 2010).

6.4 Recommendation for future work

The study has identified a number of key areas that face a decline in the potential suitability for arabica coffee over the next century (Fig. 5.5). Socio-economic factors and farm management determines resilience within communities to adapt to climatic changes (Reidsma *et al*., 2010) and studies over the past five-years have begun to establish relationships between climatic changes, crop physiological responses and economic and livelihood responses (Gay *et al*, 2006; Moriondo *et al*., 2007; Liu *et al*., 2008). This type of integrated modelling requires more detailed inputs, for example soil type, solar radiation, diurnal temperature changes and soil water holding capacity. Land-degradation, topography and access to transport networks have also been stimulated in such models. Given the relatively low resolution of this study (0.5°×0.5° grid cell locations) and the region (East Africa), the above information was difficult to obtain. This could be overcome by focusing future studies on particular regions of specific countries, and include collection of farm and field-level data. Yates *et al*. (2010b), suggests that to improve future species distribution models, increasing field work and monitoring may be required. Including economic variables such as world coffee price, local wages and GDP as Gay *et al*. (2006) did would improve the predictability of models.

This study was only able to identify areas of potential suitability based upon mean annual temperatures and total precipitation. Only country-level annual yield data and actual arabica coffee distribution information for Ethiopia was available. The bioclimatic envelope model over-estimated the number of current locations suitable for arabica coffee in Ethiopia (Fig. 3.10). Utilisation of remotely sensed satellite data in future studies could give more detailed information about topographic variation, land degradation, current land-use and land access, including local transport networks. This information could be used to access the suitability of an area for coffee production and combined with climatic data.

Future studies should be focused upon particular arabica coffee growing areas within Ethiopia, Tanzania and Malawi that are most at risk from future changes in mean annual temperatures and total annual precipitation. Using data from individual coffee cooperatives would provide access to longer-term yield information, as each producer is likely to keep records of past production. Information from local weather stations would improve the accuracy of models and predictions made. Higher spatial resolution data and mapping of current arabica coffee producing areas would improve understanding of potential future suitability. To assess the future productivity of arabica coffee and potential yields, economic factors should be included in regression based models (Gay *et al*., 2006).

Chapter Seven

Conclusions

Over the 21st century global mean annual temperatures are expected to increase. Changes in precipitation are expected, with some areas becoming wetter and others drier. Variation in precipitation will increase, with climatic extremes such as drought and floods becoming increasingly commonplace. These changes will affect the distribution of species with presently occupied areas becoming unsuitable and new regions of climatic suitability emerging. Crop yields and quality will be affected by climatic extremes, increases in temperatures, and precipitation variation. To ensure food security and the maintenance of economically viable yields of commodity crops, growers will have to adapt farming practices to mitigate the effects of future climatic change.

This study examined the spatial distribution of past and future regions of climatic suitability for arabica coffee, a very economically and socially important commodity crop in East Africa. Optimal conditions for arabica coffee growth were identified as areas with mean annual temperatures of between 18°C and 22°C and total annual precipitation of between 1200mm and 1800mm. In this study tolerable growing conditions were identified as regions with mean annual temperatures of between 15°C and 30°C and total annual precipitation between 800mm and 2500mm. This study showed that mean annual temperatures have increased and total precipitation has decreased over the past 40 years. This has coincided with a decline in the number of both climatically optimal and tolerable locations suited to arabica coffee cultivation in all of the eight countries studied.

Using a bioclimatic envelope model and future climatic data from three global circulation models, the future number and distribution of optimal and tolerable coffee growing locations were identified. Results suggest that there will be a further decline in the number of optimal locations in the future. Regions in Malawi, Tanzania, Uganda and Zambia will be the most affected. Up until 2020, precipitation is the limiting factor in the number of optimal locations, and adaption strategies should address water management issues. Beyond 2020, temperature is the limiting factor, with much of East Africa experiencing mean monthly temperatures in excess of 25°C.

However, the number of locations with tolerable climatic conditions for arabica coffee increases from the present day, when future climatic data from the CSIRO3 and Echam5 global circulation models are used. The HadGEM model is a ‘drier’ model and suggests less precipitation in the future than the other global circulations models. This results in a future decline in the number of tolerable sites for arabica coffee.

Kenya is predicted to lose the highest percentage of tolerable coffee growing locations of any country studied.

Throughout the time period studied, both past and future, very few new areas of areas of suitability for arabica coffee emerge in East Africa. These areas of new suitability are limited to tolerable sites, and no new optimal regions occur. Optimal conditions for arabica coffee production are presently at the extreme of the climatic conditions experienced in East Africa. Further rises in temperature and no significant increase in precipitation results in a decline in optimal areas for *C. arabica* cultivation.

Arabica coffee yields in East Africa over the past 40 years have changed, and generally show a peak in the late 1980s before declining over the last two decades. We found that June-July-August (JJA) temperature, and March-April-May (MAM) precipitation were highly correlated with arabica coffee yields. Using seasonal climatic variables a multiple regression model was developed, but this was unable to account for much of the variation in arabica coffee yields. Other bioclimatic variables and economic factors could be included if developing regression models in future studies.

Analysing future climatic trends and seasonal variations led to a conclusion that the productivity of arabica coffee in most parts of East Africa will be negatively affected by rising mean temperatures and seasonal precipitation variation. From previous studies, it was noted that farmers are often unaware of the vulnerability and risk that longer term climatic change poses, and this should be addressed through education and making knowledge easily accessible and available in rural areas of East Africa.

Overall, this study has shown that mean annual temperature and total annual precipitation can be used as indicators to suggest potential areas that are climatically suitable for arabica coffee production currently, and in the future. Changes in these climatic variables over the next century will result in a decline in the number of optimal locations in East Africa, and a loss of current forest and garden coffee areas in Ethiopia. Future temperatures exceeding 25ºC will have a damaging effect on arabica coffee plants, and may result in declining yields. Malawi, Tanzania and Zambia are the countries that are expected to lose the highest percentage of present day optimal locations. Adaptation strategies to mitigate future changes in climate should be explored.

Bibliography:

AdapCC (2009) Adaption for Smallholders to Climate Change. URL: www.adapcc.org (accessed 14/4/09).

Alègre, C. (1959). Climates et caféiers d'Arabie. *Agron. Trop*. 14: 23-58. Cited from: DaMatta, F.M., (2004) Ecophysiological constraints on the production of shaded and unshaded coffee: a review. *Field Crop Research*, 86. 99-114.

Alvium, P. T. (1960) Moisture stress as a requirement for flowering of coffee. *Science*, 132: 354.

Ambinakudige, S. & Choi, J. (2009) Global coffee market influence on land-use and land-cover change in the Western Ghats of India. *Land Degradation and Development*, 20: 327-335.

Baffes, J. (2005) Tanzania's coffee sector: Constraints and Challenges. *Journal of International Development,* 17: 21-43.

Bakker, M.M., Govers, G., Ewert, F., Rounsevell, M. & Jones, R. (2005) Variability in regional wheat yields as a function of climate, soil and economic variables: Assessing the risk of confounding. *Agriculture, Ecosystems and Environment*, 110: 195-209.

Barros, R.S., da S.e Mota, J.W., Da Matta, F.M. & Maestri, M. (1997). Decline of vegetative growth in *Coffea arabica L.* in relation to leaf temperature, water potential and stomatal conductance. *Field Crops research*, 54: 65-72.

Bässler, C., Muller, J., Hothorn, T., Kneib, T., Badeck, F. & Dziock, F. (2010) Estimation of the extinction risk for high-montane species as a consequence of global warming and assessment of their sustainability as cross-taxon indicators. *Ecological Indicators*, 10: 341-352.

Beaumont, L.J., Pitman, A.J., Poulsen, M. & Hughes, L. (2007) Where will species go? Incorporating new advances in climate modelling into projections of species distributions. *Global Change Biology*, 13: 1368-1385.

Beer, J., Muschler, R., Kass, D. & Somarriba, E. (1998) Shade management in coffee and cacao plantations. *Agroforestry Systems*, 38: 139-164.

Bezabih, M., Chambwera, M., Stage, J. (2010) Climate Change, Total Factor Productivity, and the Tanzanian Economy: A Computable General Equilibrium Analysis. *Envrionment for Development Discussion Paper Series*, 10-14.

Block, P.J., Strzepek, K., Rosegrant, M.W. & Diao, X. (2008) Impacts of considering climate variability on investment decisions in Ethiopia. *Agricultural Economics*, 39: 171-181.

Blore, T.W.D. (1966) Further studies of water use by irrigation and unirrigated arabica coffee in Kenya. *Journal of Agricultural Science Cambridge*, 67: 145-154. Cited from: Descroix, F., Snoeck, J., (2004) Environmental factors suitable for coffee cultivation. In Wintgens, J.N. (Ed.) *Coffee: growing, Processing, Sustainable Production. A guide for growers, traders and researchers.* Wiley-Vch Verlag GmbH and CoKGaA, Weinheim, Germany.

Boko, M., Niang, I., Nyong, A, Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R. & Yanda, P. (2007) Africa. Climate Change 2007: Impacts, Adaptation and Vulnerability. In, Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. pp. 433-467.

Boulanger, J.P. & Penalba, O. (2010) Assessment of climate information needs in the Argentinean Agro-business sector. *Climatic Change*, 98: 551-563

Brown, M.E. & Funk, C.C. (2008) Food security under climate change. *Science*, 319: 580-581.

Cambrony, H.R. (1992) *Coffee growing.* The Macmillian Press Ltd. London

Cannell, M.G.R. (1985) Physiology of the Coffee Crop. In: Clifford, M.N., Willson, K.C., (Eds.), Coffee. Botany, Biochemistry and production of beans and beverage. Croom Helm Ltd. Beckenham. pp. 108-135.

Carmargo, A.P. (1985) O clima e a cafeicultura no Brasil. *Inf. Agropec*, 11: 13-26. Cited from: DaMatta, F.M., (2004) Ecophysiological constraints on the production of shaded and unshaded coffee: a review. *Field Crop Research*, 86: 99-114.

Cerri, C.E.P., Sparovek, G., Bernoux, M., Easterling, W.E., Melillo, J.M. & Cerri, C.C. (2007) Tropical agriculture and global warming: impacts and mitigation options. *Scientific Agriculture*, 64(1) Doi:10.1590/S1590/S0103-901620070001000313.

Challinor, A.J. (2009) Towards the development of adaptation options using climate and crop yield forecasting at seasonal to multi-decadal timescales. *Environmental Science and Policy*, 12: 453-465.

Challinor, A.J., Osborne, T.M. & Slingo, J.M. (2006) Assessing the vulnerability of crop productivity to climate change thresholds using an integrated crop-climate model. In, Scellnhuber, J., Cramer, W., Nakicenovic, N., Wigley, T. & Yohe, G. (Eds.) *Avoiding Dangerous Climate Change*. Cambridge University Press, Cambridge.

Challinor, A.J., Wheller, T., Garforth, C., Crauford, P. & Kassam, A. (2007) Assessing the vulnerability of food crop systems in Africa to climate change. *Climatic Change*, 83: 381-399.

Challinor, A.J., Ewert, F., Arnold, S., Simelton, E. & Fraser, E. (2009) Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. *Journal of Experimental Botany*, 60(10): 2775-2789.

Challinor, A.J., Osborne, T.M., Morse, A., Shaffrey, L., Wheeler, T., Weller, H. & Vidale, P.L. (2009b) Methods and resources for climate impacts research. Achieving Synergy. *Bulletin of the American Meteorological Society*, 90(6): 836-848.

Conway, D., Hanson, C.E., Doherty, R. & Persechino, A. (2007) GCM Simulations of the Indian Ocean dipole influence on East African rainfall; Present and Future. *Geophysical Research Letters*, 34: LO3705 Doi:10.1029/2006GL027597.

Craufurd, P.Q. & Wheeler, T.R. (2009) Climate change and the flowering time of annual crops. *Journal of Experimental Biology*, 60(9): 2529-2539.

Crisosto, C.H., Grantz, D.A. & Meinzer, F.C. (1992) Effects of water deficit on flower opening in coffee (*Coffea arabica L.*). *Tree Physiology*, 10: 127-139.

DaMatta, F.M. (2004) Ecophysiological constraints on the production of shaded and unshaded coffee: a review. *Field Crop Research*, 86: 99-114.

DaMatta, F.M., Maestri, M. & Barros, S. (1997) Photosynthetic performance of two coffee species under drought. *Photosynthetica*, 34(2): 257-264.

Davis, A.J., Jenkinson, L.S., Lawton, J.H., Shorrocks, B. & Wood, S. (1998) Making mistakes when predicting shifts in species range in response to global warming. *Nature*, 39: 783-786

Descroix, F. & Snoeck, J. (2004) Environmental factors suitable for coffee cultivation. In Wintgens, J.N. (ed.) *Coffee: growing, Processing, Sustainable Production. A guide for growers, traders and researchers.* Wiley-Vch Verlag GmbH and CoKGaA, Weinheim, Germany.

Dinar, A., Hassan, Mendelsohn, R. & Benhin J. (2008) Climate Change and Agriculture in Africa. Impact Assessment and Adaptation Strategies. Earthscan. London.

Diniz, L.E.C., De Fatima Raus, C., De Paula Carvalho, V., Torres, F.M., Ruas, E.A., De Davis, A.J., Jenkinson, L.S., Lawton, J.H., Shorrocks, B. & Wood, S. (1998) Making mistakes when predicting shifts in species range in response to global warming. *Nature*, 391: 783-786.

Doherty, R.M., Sitch, S., Smith, B., Lewis, S.L. & Thornton, P.K. (2010) Implications of future climate and atmospheric CO_2 content for regional biogeochemistry, biogeography and ecosystem services across East Africa. *Global Change Biology*, 16: 617-640.

Downing, T.E. (1991) Vulnerability to hunger in Africa: A climate change perspective. *Global Environmental Change*, 1(5): 365-380.

Eakin, H., Tucker, C. & Castellanos, E. (2005) Market Shocks and Climate Variability. The Coffee Crisis in Mexico, Guatemala and Honduras. *Mountain Research and Development*, 25(4): 304-309.

Eakin, H. & Wehbe, M. (2009) Linking local vulnerability to system sustainability in a resilience framework: two cases from Latin America. *Climatic Change*, 93: 355-377.

East African Fine Coffees Association (2008) EAFCA Country Chapters. URL: http://www.eafca.org/chapters.htm (accessed 26/08/09).

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A. & Karl, T.R. (2000) Climate Extremes: Observations, Modelling, and Impacts. *Science,* 289 (5487): 2068-2074.

Eitzinger, A., Laderach, P., Ovalle, O., Ramirez, J., Jarvis, A. (2010) Decision and Policy Analysis group of CIAT: Climate change adaptation and mitigation in the Kenyan coffee sector. URL: http://www.slideshare.net/ciatdapa/a-eitzinger-climate-change-adaptation-and-mitigation-in-the-kenyan-coffee-sector (accessed: 14/05/2010).

Elith, J., Graham, C.H., Anderson, R.P., Dudik, M., Ferrier, S., Guisan, A., Hijmans, R.J., Huettmann, F., Leathwick, J.R., Lehmann, A., Li, J., Lohmann, L.G., Loiselle, B.A., Manion, G., Mortiz, C., Nakamura, M., Nakazawa, Y., Overton, J., Peterson, A.,P., Phillips. S.J., Richardson, K., Scachetti-Pereira, R., Schapire, R.E., Soberon, J., Williams, S., Wisz, M.S. & Zimmermann, N.E. (2006) Novel methods improve prediction of species' distributions from occurrence data. *Ecography*, 29: 129-151.

FAO (2008) FAO/GIEWS Global Watch – 15th July 2008. URL: http://www.fao.org/giews/english/shortnews/eastafrica080715.htm (accessed 25/05/10).

FAO (2009) Agricultural Commodities by country. URL: http://faostat.fao.org/site/339/default.aspx (accessed 17/08/09).

Field, A. (2005) Discovering Statistics Using SPSS. Sage Publications, London.

Foody, G.M. (2008) Refining predictions of climate change impacts on plant species distribution through the use of local statistics. *Ecological Informatics*, 3: 228-236.

Franco, C.M. (1958) Influence of temperature on growth of coffee plant, Bulletin No. 16. IBEC Research Institute, New York, 24 pp. Cited from: DaMatta, F.M., (2004) Ecophysiological constraints on the production of shaded and unshaded coffee: a review. *Field Crop Research*, 86: 99-114.

Franco, A.M.A., Hill, J.K., Kitschke, C., Collingham, Y.C., Roy, D.B., Fox. R., Huntley, B. & Thomas, C.D. (2006) Impacts of climate warming and habitat loss on extinctions at species' low-latitude range boundaries. *Global Change Biology*, 12(8): 1545-1553.

Fraser, E.D.G. (2006) Food system vulnerability: Using past famines to help understand how food systems may adapt to climate change. *Ecological Complexity*, 3: 328-335.

Funk, C., Dettinger, M.D., Michaelsen, J.C., Verdin, J.P., Brown, M.E., Barlow, M. & Hoell, A. (2008) Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development. *PNAS*, 105(32): 11081-11086.

Gay, C., Conde, C., Eakin, H. & Villers, L. (2006) Potential impacts of climate change on agriculture: A case study of coffee production in Veracruz, Mexico. *Climatic Change*, 79: 259-288.

Ghoshray, A. (2010) The extent of the world coffee market. *Bulletin of Economic Research*, 62(1): 97-107.

Giordano, P.F., Navarro, J.L. & Martella, M.B. (2010) Builidng large-scale explicit models to predict the distribution of suitable habitat patches for the Greater rhea (Rhea americana), a near-threatened species. *Biological Conservation*, 143: 357-365.

Gole, T.W., Borsch, T., Denich, M. & Tekatay, D. (2008) Floristic composition and factors characterizing coffee forests in southwest Ethiopia. *Forest Ecology and Management*, 255: 2138-2150.

Gregory, P.J., Johnson, S.N., Newston, A.C. & Ingram, J.S. (2009) Integrating pests and pathogens into the climate change/food security debate. *Journal of Experimental Botany*, 60(10): 2827-2838.

GRID (2002) Vital Climate Graphics Africa. *Global Resource Information Database, Arendal.* 2002. Available at: http://www.grida.no/climate/vitalafrica/english/23.htm (accessed: 28/07/2009).

Guisan, A. & Zimmermann, N.E. (2000) Predictive habitat distribution models in ecology. *Ecological modelling*, 135: 147-186.

Guisan, A. & Thuiller, W. (2005) Predicting species distribution: offering more than simple habitat models. *Ecology Letters*, 8: 993-1009.

Gutierrez, M.V. & Meinzer, F.C. (1994) Estimating Water Use and Irrigation Requirements of Coffee in Hawaii. *Journal of American Horticultural Science*, 119(3): 652-657.

Hafner, S. (2003) Trends in maize, rice and wheat yields for 188 nations over the past 40 years: a prevalence of linear growth. *Agriculture, Ecosystems and Environments*, 97: 275-283.

Hannah, L., Midgley, G.F. & Millar, D. (2002) Climate change-integrated conservation strategies. *Global Ecology and Biogeography*, 11: 485-495.

Hay, S.I., Cox, J., Rogers, D.J., Randolp, S.E., Stern, D.I., Shanks, G.D., Myers, M.F. & Snow, R.W. (2002) Climatic change and the resurgence of malaria in the East Africa highlands. *Nature*, 415: 905-909.

Hegazy, A.K., Medany, M.A., Kabiel, H.F. & Maez, M.M. (2008) Spatial and temporal projected distribution of four crop plants in Egypt. *Natural Resources Forum*, 32: 316-326.

Hill, J.K., Thomas, C.D., Fox, R., Telfer, M.G., Willis, S.G., Asher,J. & Huntley, B. (2002) Responses of butterflies to twentieth century climate warming: implications for future ranges. *Proc. R. Soc. Lond B.,* 269: 2163-2171.

Howden, S.M., Soussana, J.F., Tubiello, F.N., Chhetri, N., Dunlop, M. & Meinke, H. (2007) adapting agriculture to climate change. *PNAS*, 105(50): 19691-19696.

Hulme, M., Doherty, R., Ngara, T., New, M. & Lister, D. (2001) African Climate Change: 1900-2100. *Climate Research,* 17: 145-168.

Huntingford, C., Lambert, F.H., Gash, J.H.C., Taylor, C.M. & Challinor, A.J. (2005) Aspects of climate change prediction relevant to crop productivity. *Phil. Trans. R. Soc. B.* 360: 1999-2009.

Huntley, B., Berry, P.M., Cramer, C. & McDonald, A.P. (1995) Modelling present and potential future ranges of some European higher plants using climate response surfaces. Journal of Biogeography, 22: 967-1001.

Iglesias, A., Rosenzweig, C. & Pereira, D. (2000) Agricultural impacts of a climate change in Spain: developing tools for a spatial analysis. *Global Environmental Change*, 10(1): 69-80.

iKhofi (2009) URL:
http://www.ikhofi.co.za/amaphepha/ethiopian_coffee/production_methods.htm
(accessed 02/04/2009).

Ingram, J.S.I., Gregory, P.J. & Izac, A-M. (2008) The role of agronomic research in climate change and food security policy. *Agriculture Ecosystems and Environment*, 12: 4-12.

IPCC (2007) Summary for Policymakers. In, Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M, Averyt, K.B., Tignor, M. & Miller, H.L. (Eds.) Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Jaramillo, J., Chabi-Olaye, A., Kamonjo, C., Jaramillo, A., Vega, F.E., Poehling, H.M. & Borgemeister, C. (2009) Thermal tolerance of the Coffee Berry Borer *Hypothenemus hampei:* predictions of climate change impact on a tropical insect pest. *PLOS One*, 4(8): e6487 Doi:10.1371/journal.pone.0006487.

Jones, P.G. & Thornton, P.K. (2009) Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environmental Science and Policy*, 12: 427-437.

Kaser, G., Hardy, D.R., Mölg, T., Bradley, R.S. & Hyera, T.M. (2004) Modern Glacier Retreat on Mt Kilimanjaro as Evidence of Climatic Change: observations and facts. *International Journal of Climatology*, 24: 329-339.

Klein, A.M., Steffan-Dewenter,I. & Tscharntke, T. (2002) Fruit set of highland coffee increases with the diversity of pollinating bees. *Phil. Trans. R. Soc. B.,* 270: 955-961.

Labouisse, J.P; Bellachew, B., Kotecha, S. & Bertrand, B. (2008) Current statues of coffee (*Coffea arabica L.)* genetic resources in Ethiopia: implications for conservation. *Genetic Resources Crop Evolution*, 55: 1079-1093.

Lhomme, J.P., Mougou, R. & Mansour, M. (2009) Potential impact of climate change on durum wheat cropping in Tunisia. *Climatic Change*, 96: 549-564.

Lin, B. (2007) Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. *Agricultural and Forest Meteorology*, 144: 85-94.

Lin, B.B. & Richards, P.L. (2007) Soil random roughness and depression storage on coffee farms of varying shade levels. *Agricultural Water Management*, 92(3): 194-204 Doi:10.1016/j.agwat.2007.05.014.

Lipp, E.K., Huq, A. & Colwell, R.R. (2002) Effects of global climate on infectious disease: the cholera model. Clinical Microbiology Reviews, 15(4): 757-770.

Liu, C., Berry, P.M., Dawson, T.P. & Pearson, R.G. (2005) Selecting thresholds of occurrence in the prediction of species distributions. *Ecography*, 28: 385-393.

Liu, L., Williams, J.R., Zehnder, A.J.B. & Yang, H. (2007) GEPIC – modelling what yield and crop water productivity with high resolution on a global scale. *Agricultural Systems*, 94: 478-493.

Liu, J., Fritz, S., van Wesenbeeck,C.F.A., Fuchs,F., You, L., Obersteiner, M. & Yang, H. (2008) A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change. *Global and Planetary Change*, 64: 222-235.

Lobell, D. & Field, C.B. (2007) Global scale climate-crop yield relationships and impacts of recent warming. *Environmental Research Letters*, 2(1): 014002 Doi:10.1088/1748-9326/2/1/014002.

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P. & Naylor, R.L. (2008) Prioritizing Climate Change Adaptation Needs for Food Security in 2030. *Science*, 319: 607-610.

Maestri, M. & Barros, R.S. (1977) Coffee. In: Alvium, P.T., Kozlowski, T.T. (Eds.), Ecophysiology of Tropical Crops. Academic Press, New York, pp.249-278. Cited from: DaMatta, F.M., (2004) Ecophysiological constraints on the production of shaded and unshaded coffee: a review. *Field Crop Research*, 86: 99-114.

Mendelsohn, R., Morrison, W., Schlesinger, M.E. & Andronova, N.G. (2000) Country-specific market impacts from climate change. *Climatic Change*, 45: 553-569.

Mertz, O., Mbow, C., Reenberg, A. & Diouf, A. (2009) Farmers' Perceptions of Climate Change and Agricultural Adaption Strategies in Rural Sahel. *Environmental Management*, 43: 804-816.

Mitchell T.D. & Jones P.D. (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Climatol*, 25: 693-712.

Montoya, D., Purves, D.W., Urbieta, I.R. & Zavala, M.A. (2009) Do species distribution models explain spatial structure within tree species ranges? *Global Ecology and Biogeography*, 18(6): 662-673.

Montoya, J.M. & Raffaelli, D. (2010) Climate change, biotic interactions and ecosystem services. *Phil. Trans. R. Soc. B*, 365(1549): 2013-2018 Doi:10.1098/rstb.2010.0114.

Moriondo, M., Maselli, F. & Bindi, M. (2007) A simple model of regional what yield based on NDVI data. *European Journal of Agronomy*, 26: 266-274.

New, M., Hulme, M. & Jones, P. (2000) Representing Twentieth-Century Space-Time Climate Variability. Part II: Development of 1901-96 Monthly Grids of Terrestrial Surface Climate. *Journal of Climate*, 13(13): 2217-2238.

Nicholls, N. (1997) Increased Australian wheat yield due to recent climate trends. *Nature*, 387: 484-485.

Ohlemüller, R., Gritti, E.S., Sykes, M.T. & Thomas, C.D. (2006) Quantifying components of risk for European woody species under climate change. *Global Change Biology*, 12(9): 1788-1799.

Ortiz, R., Sayre, K.D., Govaerts, B., Gupta, R., Subbarao, G.V., Ban, T., Hodson, D., Dixon, J.M., Ortiz-Monasterio, J.I. & Reynolds, M. (2008) Climate change: Can wheat beat the heat? *Agriculture, Ecosystems and Environment*, 126: 46-58.

Osborne, T.M., Lawrence, D.M., Challinor, A.J., Slingo, J.M., Wheeler, T.R. (2007) Development and assessment of a coupled crop-climate model. *Global Change Biology,* 13: 169-183.

Parmesan, C., Ryrholm, N., Stefanescu, C., Hill, J. K., Thomas, C. D., Descimon, H., Huntley, B., Kalia, L., Kullberg, K., Tammaru, T., Tennent W. J., Thomas, J. A. & Warren, M. (1999) Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature,* 399(6736): 579-583.

Parmesan, C. & Yone, G. (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 421(6918): 37-42.

Parry. M.L., Rosenzweig, C., Iglesias, A., Livermore, M. & Fischer, G. (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change*, 14: 53-67.

Parry, M.L., O.F. Canziani, J.P. Palutikof & Co-authors (2007) Technical Summary. *Climate Change 2007: Impacts, Adaptation and Vulnerability.* In, Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. pp. 23-78.

Pearson, R.G. & Dawson, T.P. (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography*, 12(5): 361-371 Doi:10.1046/j.1466-822x.2003.00042.x.

Penman, T.D., Pike, D.A., Webb, J.K. & Shine, R. (2010) Predicting the impacts of climate change on Australia's most endangered snake, *Hoplocephalus bungaroides. Diversity and Distributions*, 16: 109-118.

Petit, N. (2007) Ethiopia's coffee sector: A bitter or better future? *Journal of Agrarian Change*, 7(2): 225-261.

Pielke, R.A., Avissar, R., Raupach, M., Dolman, J., Zeng, A., Denning, A.S. (1998) Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. *Global Change Biology,* 4: 461-475.

Porter, J.R. & Semenov, M.A. (2005) Crop responses to climatic variation. *Phil. Trans. R. Soc. B.,* 360: 2021-2035.

Prentice, I.C., Cramer, W., Harrison, S.P., Leemans, R., Monserud, R.A. & Solomon, A.M. (1992) A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography*, 19: 117-134.

Pyke C.R., Andelman, S.J. & Midgley, G. (2005) Identifying priority areas for bioclimatic representation under climate change: a case study for Proteacae in the Cape Florisitc Region, South Africa. *Biological Conservation*, 125: 1-9.

Reidsma, P., Ewert, F., Lansink, A.O. & Leemans, R. (2010) Adaptation to climate change and climate variability in European agriculture: The importance of farm level responses. *European Journal of Agronomy*, 32: 91-102.

Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q. G., Casassa, G., Menzel, A., Root, T. L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C. Z.,

Rawlins, S. & Imeson, A. (2008) Attributing physical and biological impacts to anthropogenic climate change. *Nature*, 453(7193): 353-358.

Rost, S.F., Gerten, D., Hoff, H., Lucht, W., Falkenmark, M. & Rockström, J. (2009) Global potential to increase crop production through water management in rainfed agriculture. *Environmental Research Letter*, 4(4): 044002 Doi:10.1088/1748-9326/4/4/044002.

Rutherford, M. (2006) Current knowledge of coffee wilt disease, a major constraint to coffee production in Africa. *Phytopathology*, 96(6): 663-666.

Santika, T. & Hutchinson, M.F. (2009) The effect of species response form on species distribution model prediction and inference. *Ecological Modelling*, 220: 2365-2379.

Schlenker, W. & Lobell, D. (2010) Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 5(1): 014010 Doi:10.1088/1748-9326/5/1/014010.

Schmidhuber, J. & Tubiello, F.N. (2007) Global food security under climate change. *PNAS*, 104(50): 19703-19708.

Schmitt, C.B., Senbeta, F., Denich, M. & Preisinger, H. (2009) Wild coffee management and plant diversity in the montane rainforest of south-western Ethiopia. *African journal of Ecology*, 48: 78-86.

Schröter, D., Cramer, W., Leemans, R., Prentice, I.C., Araújo, M.B., Arnell, N.W., Bondeau, A., Bugmann, H., Carter, T.R., Gracia, C.A., de la Vega-Leinert, A.C., Erhard, M., Ewert, F., Glendining, M., House, J.I., Kankaanpää, S., Klein, R.J.T., Lavorel, S., Linder, M., Metzger, M.J., Meyer, J., Mitchell, T.D., Reginster, I., Rounsevell, M., Sabaté, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M.T., Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S. & Zierl, B. (2005) Ecosystem Service Supply and Vulnerability to Global Change in Europe. *Science*, 310: 1333-1337.

Senbeta, F. & Denich, M. (2006) Effects of wild coffee management on species diversity in the Afromontane rainforests of Ethiopia. *Forest Ecology and Management*. 232: 68-74.

Senbeta, F., Denich, M., Boehmer, H.J., Woldemariam, T., Teketay, D. & Demissew, S. (2007) Wild *Coffea arabica L.* in the Afromontane rainforests of Ethiopia: Distribution, Ecology and Conservation. *Ethiopian Journal of Science*, 30(1): 13-24.

Soini, E. (2005) Land use change patterns and livelihood dynamics on the slopes of Mt. Kilimanjaro, Tanzania. *Agricultural Systems*, 85: 306-323.

Slingo, J.M., Challinor, A.J., Hoskins, B.J. & Wheeler, T.R. (2005) Introduction: food crops in a changing climate. *Philosophical transactions of the Royal Society B.*, 360: 1983-1989.

Stehfest, E., Heistermann, M., Priess, J.A., Ojima, D.S. & Alcamo, J. (2007) Simulation of global crop production with the ecosystem model DayCent. *Ecological Modelling*, 209: 203-219.

Stockle, C.O., Donatelli, M. & Nelson, R. (2003) CropSyst, a cropping system simulation model. *European Journal of Agronomy*, 18: 289-307.

Sykes, M.T., Prentice, I.C. & Cramer, W. (1996) A bioclimatic model for the potential distributions of north European tree species under present and future climates. *Journal of Biogeography*, 23: 203-233.

Tabor, K. & Williams, J.W. (2010) Globally downscaled climate projections for assessing the conservation impacts of climate change. *Ecological Applications*, 20(2): 554-565.

Teketay, D. (1999) History, Botany and Ecological Requirements of Coffee. *Walia*, 20: 28-50.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., De Siqueria, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huenta, M.A., Peterson, A.T., Phillips, O.L. & Williams, S.E. (2004) Extinction risk from climate change. *Nature*, 437: 145-148.

Thomas, C.D., Franco, A.M.A. & Hill, J.K. (2006) Range retractions and extinctions in the face of climate warming. *Trends in Ecology and Evolution*, 21(8): 415-416.

Thornton, P.K., Jones, P.G., Algarswamy, G. & Andresen, J. (2009) Spatial variation of crop yield response to climate change in East Africa. *Global Environmental Change*, 19: 54-65.

Thornton, P.K., Jones, P.G., Algarswamy, G., Anderson, J. & Herrero, M. (2010) Adapting to climate change: Agriculture system and household impacts in East Africa. *Agricultural Systems*, 103(2): 73-82.

Thuiller, W., Lavorel, S., Araújo, M.B., Sykes, M.T. & Prentice, I.C. (2005) Climate change threats to plant diversity in Europe. *PNAS*, 102(23): 8245-8250.

Tubiello, F.N., Soussana, J-F. & Howden, S.M. (2007) Crop and pasture response to climate change. *PNAS*, 104(50): 19686-19690.

Tucker, C.M., Eakin, H. & Castellanos, E.J. (2010) Perceptions of risk and adaptation: Coffee producers, market shocks, and extreme weather in Central America and Mexico. *Global Environmental Change*, 20: 23-32.

UNDP (2008) Human Development Indices: A Statistical Update 2008. URL: http://hdr.undp.org/en/statistics/ (accessed 17/08/09).

UN Population Division (2008) Department of Economic and Social Affairs Population Division. URL: http://www.un.org/esa/population/ (accessed 17/08/09).

Verpoorten, M. (2009) Household coping in war-and peacetime: Cattle sales in Rwanda, 1991-2001. *Journal of Development Economics*, 88(1): 67-86.

Walker, N.J. & Schulze, R.E. (2008) Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. *Agriculture, Ecosystems and Environment*, 124: 114-124.

Waller, J.M. (1985) Control of Coffee Diseases. In: Clifford, M.N., Willson, K.C., (Eds.), Coffee. Botany, Biochemistry and production of beans and beverage. Croom Helm Ltd., Beckenham. pp. 219.

Wiersum, K.F., Gole, T.W., Gatzweiler, F., Volkmann, J., Bognetteau, E. & Wirtu, A.O. (2008) Certification of wild coffee in Ethiopia: Experiences and Challenges. *Forests, Trees and Livelihoods*, 18: 9-21.

Willson, K.C. (1985) Cultural Methods. In: Clifford, M.N., Willson, K.C., (Eds.), Coffee. Botany, Biochemistry and production of beans and beverage. Croom Helm Ltd., Beckenham. pp. 97-108.

Wisz, M., Dendoncker, N., Madsen, J., Rounsevell, M., Jespersen, M., Kuijken, E., Courtens, W., Verscheure, C. & Cottar, F. (2008) Modelling pink-footed goose (*Anser brachyrhynchus*) wintering distributions for the year 2050: potential effects of land-use change in Europe. *Diversity and Distributions*, 14: 721-731.

Woodward, F.I. (1987) Climate and plant distribution. Cambridge University Press, Cambridge.

Wrigley, G. (1988) Coffee. Longman Scientific and Technical, Harlow.

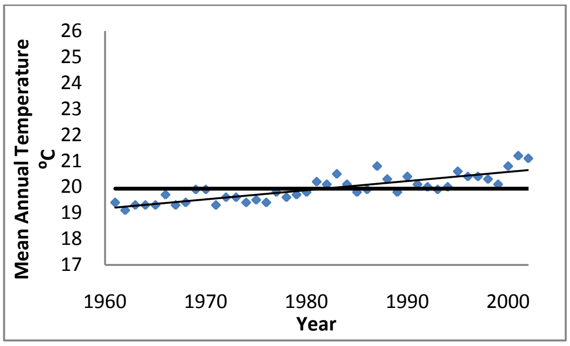
Wrigley, G. (1995) Coffee. In: Smart, J., Simmonds, N.W. (Eds.), Evolution of crop plants. Longman Scientific and Technical, Harlow. pp. 438-443.

Yates, C.J., McNeill, A., Elith, J. & Midgley, G.F. (2010a) Assessing the impacts of climate change and land transformation on *Banksia* in the South West Australian Florisitc region. *Diversity and Distributions*, 16: 187-201.

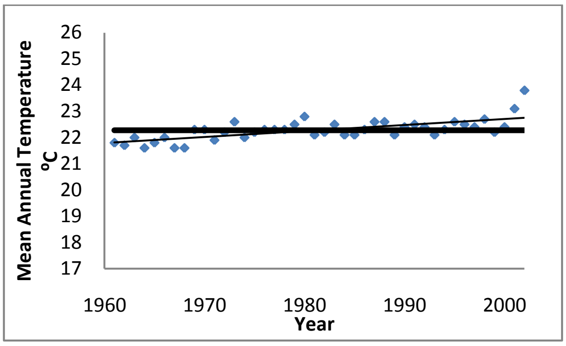
Yates, C. J., Elith, J., Latimer, A. M., Le Maitre, D., Midgley, G. F., Schurr, F. M. & West, A. G. (2010b) Projecting climate change impacts on species distributions in megadiverse South African Cape and Southwest Australian Floristic Regions: opportunities and challenges. *Austral Ecology*, 35(4): 374-391.

You, L., Wood, S. & Wood-Sichra, U. (2009) Generating plausible crop distribution maps for Sub-Saharan Africa using a spatially disaggregated data fusion and optimization approach. *Agricultural Systems*, 99: 126-140.

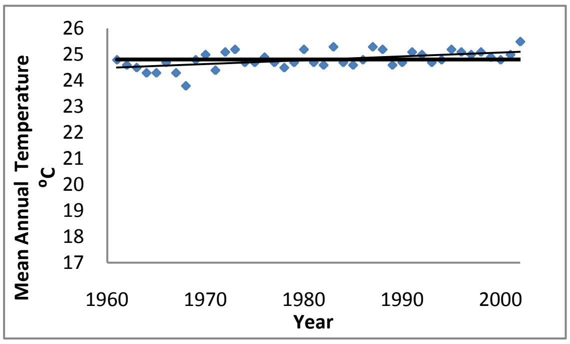
APPENDIX ONE – Climatic trends in East Africa from 1961-2002



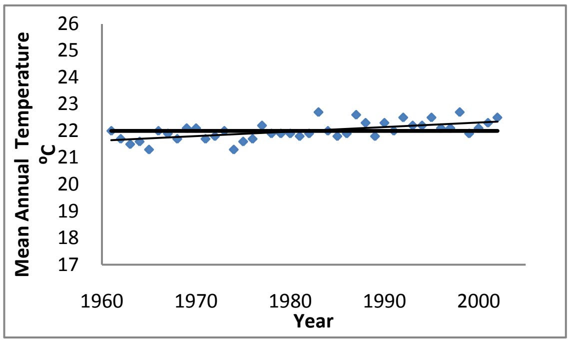
a) Burundi (Mean= 19.9°C)



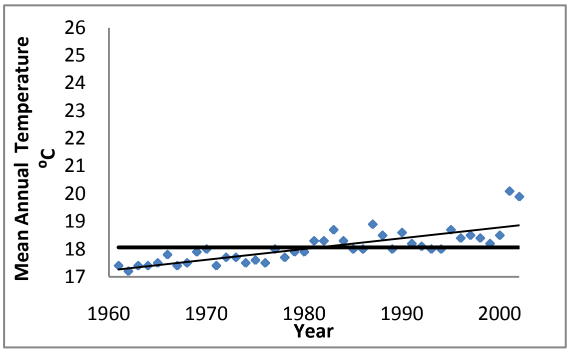
b) Ethiopia (Mean= 22.3°C)



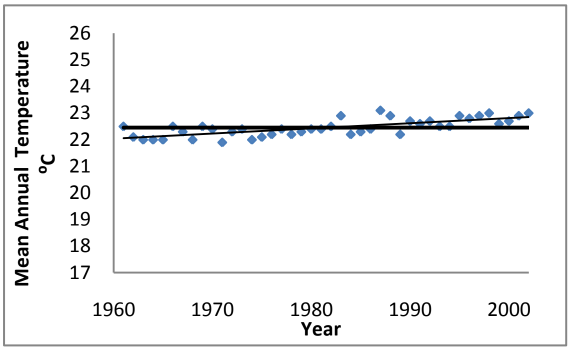
c) Kenya (Mean = 24.8°C)



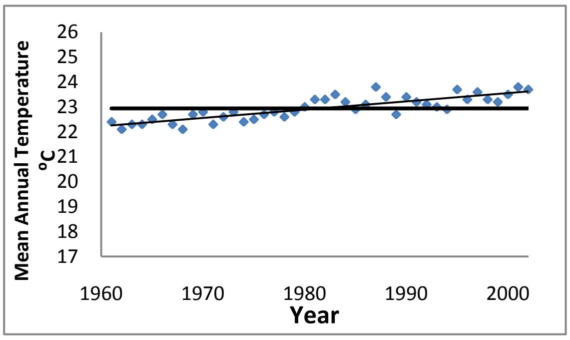
d) Malawi (Mean= 22°C)



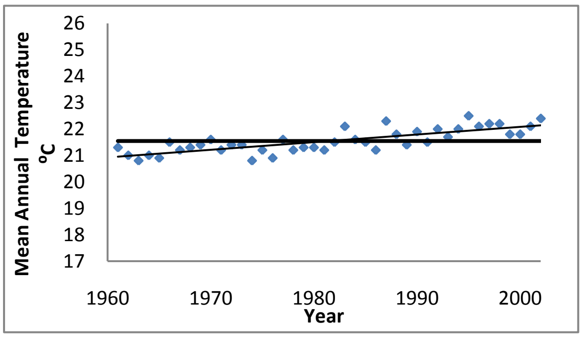
e) Rwanda (Mean= 18.1°C)



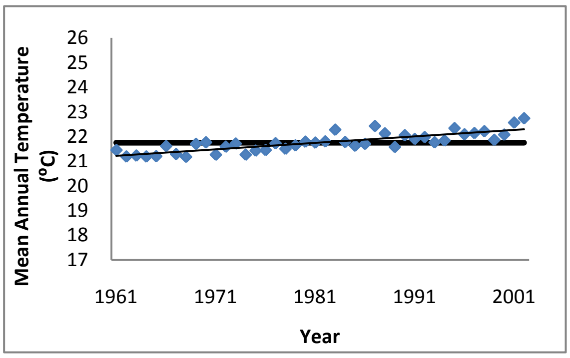
f) Tanzania (Mean = 22.5°C)



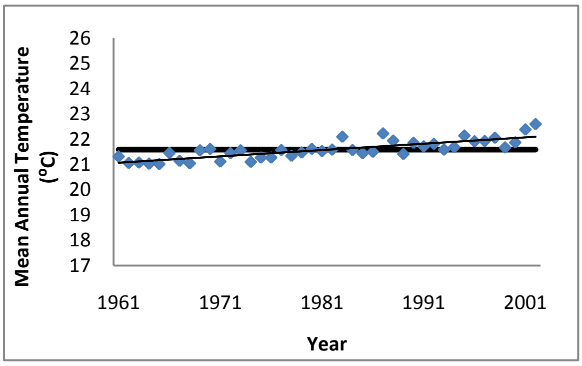
g) Uganda (Mean= 22.9°C)



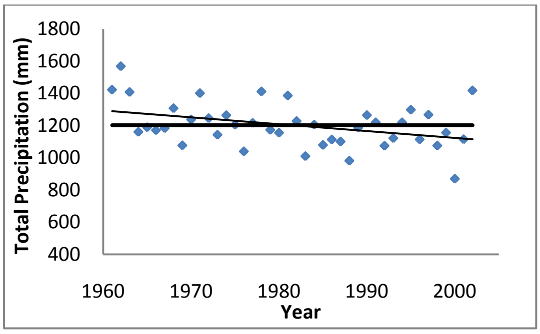
h) Zambia (Mean=21.6°C)



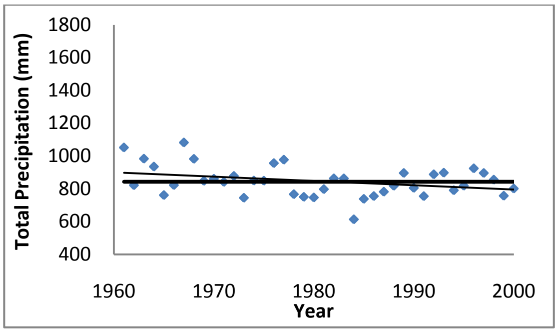
i) All countries including Rwanda (Mean= 21.8°C)



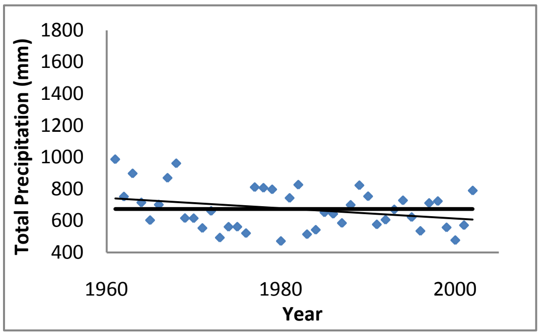
j) All countries exclduing Rwanda (Mean=21.6°C)



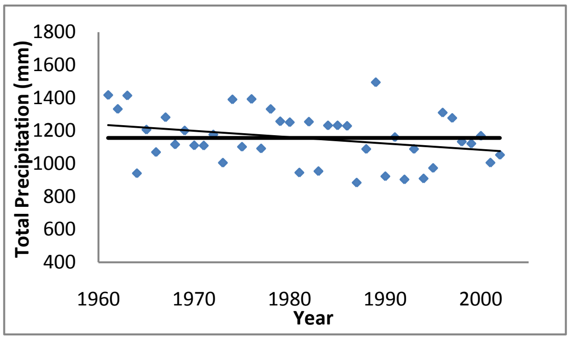
a) Burundi (Mean= 1202mm)



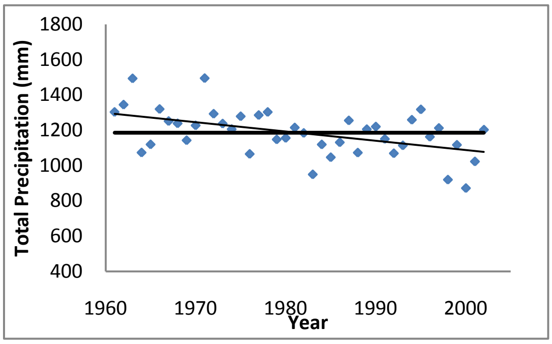
b) Ethiopia (Mean= 843mm)



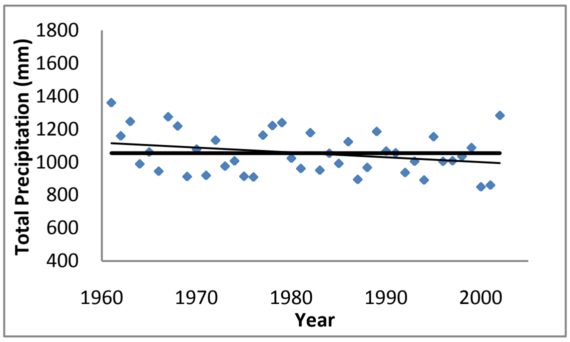
c) Kenya (Mean= 675mm)



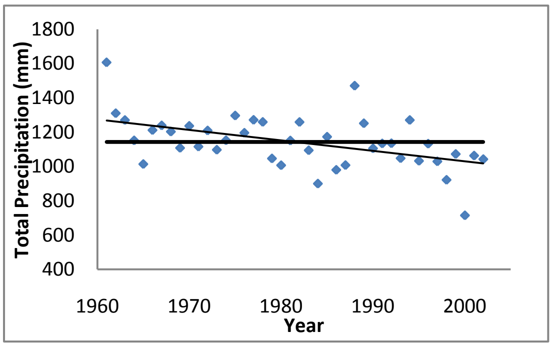
d) Malawi (Mean= 1155mm)



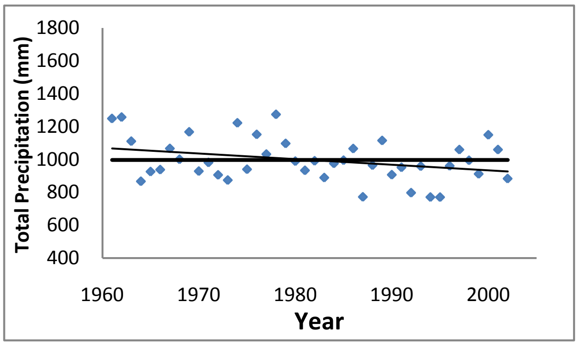
e) Rwanda (Mean= 1185mm)



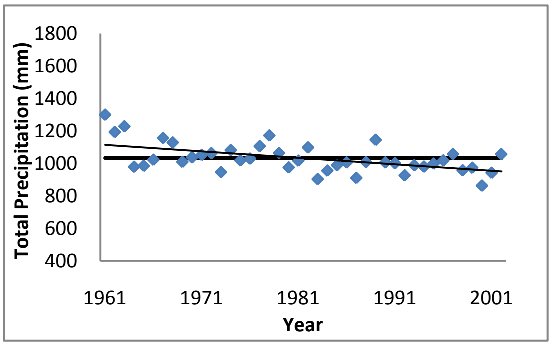
f) Tanzania (Mean= 1054mm)



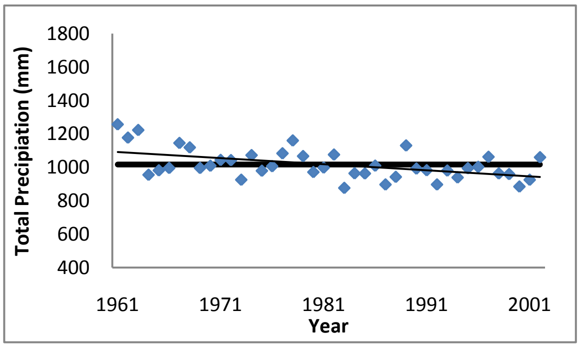
g) Uganda (Mean=1143mm)



h) Zambia (Mean= 996mm)



i) All countries including Uganda (Mean= 1032mm)



j) All countries excluding Uganda (Mean=1016mm)

APPENDIX TWO: The Spearman's Rho correlation coefficients between all climatic variables considered

Seasonal Temp variables:	MAM Temp	MAM Temp Yr – 1	JJA Temp	JJA Temp Yr – 1	SON Temp	SON Temp Yr – 1	DJF Temp	DJF Temp Yr – 1	MAM Precip	MAM Precip Yr – 1	JJA Precip	JJA Precip Yr – 1	SON Precip	SON Precip Yr – 1	DJF Precip	DJF Precip Yr – 1
MAM Temp	1.00															
MAM Temp Yr – 1	0.92*	1.00														
JJA Temp	0.88*	0.85*	1.00													
JJA Temp Yr – 1	0.86*	0.87*	0.97*	1.00												
SON Temp	0.42*	0.40*	0.11	0.09	1.00											
SON Temp Yr – 1	0.40*	0.42*	0.09	0.11	0.93*	1.00										
DJF Temp	0.58*	0.56*	0.34*	0.33*	0.84*	0.80*	1.00									
DJF Temp Yr – 1	0.62*	0.58*	0.35*	0.34*	0.83*	0.84*	0.89*	1.00								
Seasonal Precip variables:																
MAM Precip	-0.38*	-0.26*	-0.16*	-0.11	-0.33*	-0.31*	-0.15	-0.15*	1.00							
MAM Precip Yr – 1	-0.28*	-0.35*	-0.14*	-0.16	-0.33*	-0.34*	-0.15	-0.15	0.60*	1.00						
JJA Precip	0.65*	0.65*	0.77*	0.80*	-0.29*	-0.28*	-0.01	0.01	-0.04	-0.06	1.00					
JJA Precip Yr – 1	0.64*	0.66*	0.78*	0.79*	-0.27*	-0.29*	0.02	-0.01	0.18*	-0.04	0.91*	1.00				
SON Precip	0.04	0.05	0.31*	0.30*	-0.56*	-0.52*	-0.34*	-0.33*	0.17*	0.19*	0.48*	0.50*	1.00			
SON Precip Year – 1	0.05	0.04	0.30*	0.30*	-0.51*	-0.57*	-0.33*	-0.34*	0.20*	0.19*	0.48*	0.48*	0.67*	1.00		
DJF Precip	-0.67*	-0.67*	-0.85*	-0.85*	0.21*	0.20*	-0.01	-0.03	0.19*	0.20*	-0.85*	-0.81*	-0.40*	-0.45*	1.00	
DJF Precip Yr – 1	-0.69*	-0.68	-0.85*	-0.84*	0.21*	0.22*	0.00	-0.02	-0.16*	0.20*	-0.85*	-0.85*	-0.48*	-0.40*	0.89*	1.00

Annual variables:	Mean Annual Temp	Mean Temp Yr – 1	Total Annual Precip	Total Precip Yr - 1	3-Yr Average Temp	3-Yr Average Total Precip
Mean Annual Temp	1.00					
Mean Temp Yr – 1	0.92*	1.00				
Total Annual Precip	-0.51*	-0.44*	1.00			
Total Precip Yr - 1	-0.48*	-0.52*	0.67*	1.00		
3-yr average variables:						
3-Yr Average Temp	0.96*	0.87*	-0.61*	-0.56*	1.00	
3-Yr Average Total Precip	-0.55*	-0.53*	0.88*	0.88*	0.53*	1.00

*Correlation is significant at p=<0.01