Plant conservation in space, time and a changing world: forecasting the fate of *Coffea arabica* in Ethiopia

Thesis Submitted for degree in Doctor of Philosophy, School of Geography, University of Nottingham

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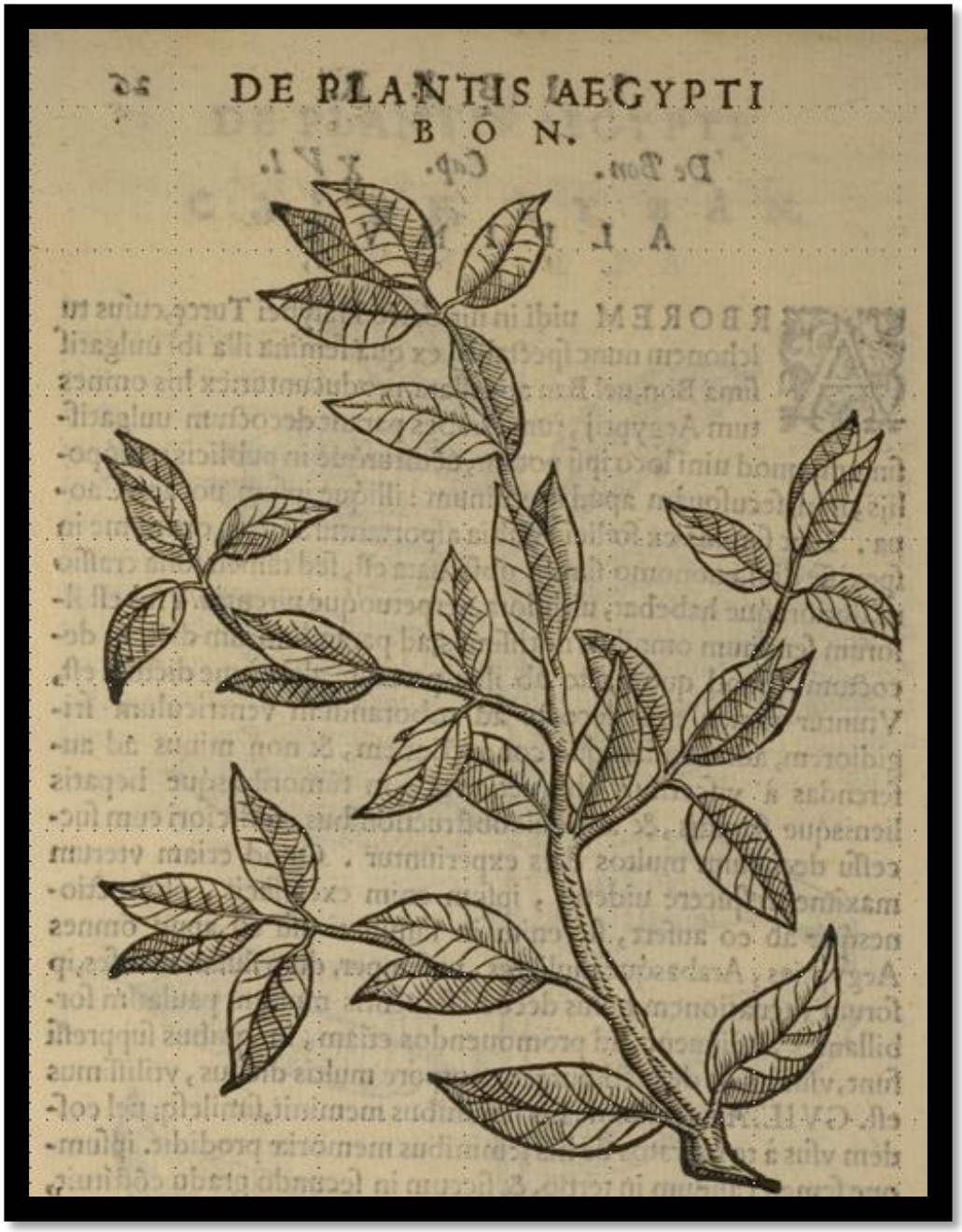


Figure 1. Black and white plate of Coffea arabica from Prospero Alpino "De Medicina Aegyptiorum" (1591).

Although formally published as Coffea arabica *by Linnaeus in 1753,* C. arabica *was known to the scientific and medical community in the sixteenth and seventeenth centuries and had been consumed for many centuries (if not millennia) before this.*

Abstract

We are facing an ever-increasing environmental crisis on our planet, with multiple threats from humankind. Industrialisation, deforestation, overpopulation and exploitation of our natural resources is driving species to extinction and changing the environment we live in. We need to plan for the future in order to adapt or mitigate against these risks. Recent advances in computing and analytical techniques, plus the rise of readily available spatial data, provide us with a means to understand the complex interactions between species, environmental change and human activity.

Coffea arabica (Arabica coffee) is a critically important crop species in several tropical countries. Globally its export value is over $13 billion dollars per year. Wild populations of this species are of immense importance to the global coffee sector, due to the traits associated with the standing genetic diversity, such as disease resilience, new flavour profiles, and agronomically favourable morphological variation (root length; compact habit). In its countries of origin, Ethiopia and South Sudan, the wild species provides the planting stock for a multi-million-dollar export sector. Arabica coffee is well known across the globe, as the increasingly popular beverage coffee. The ubiquitous cultural nature of coffee drinking means that coffee acts as a flagship species for demonstrating science and the benefits of conservation and sustainable use, enabling the findings of this thesis to gain traction with a wider audience, who might otherwise not engage with research, and social and environmental issues.

Coffea arabica is greatly influenced by climate. The wild and cultivated variants of this species are restricted to a relatively narrow climate niche, within Ethiopia and anywhere where it is cultivated. Coffee production is considerably influenced by changes in rainfall, temperature or seasonality. Ethiopia has already experienced climate change; mean temperatures from the 1960s onwards show an average increase of 0.28 °C per decade, a shortening wet season, and an increase in the number of hot days. The continuation of this rapid change in climate will influence both wild populations and production of Arabica coffee in Ethiopia.

Within this thesis I forecast the fate of wild and cultivated Arabica coffee in Ethiopia, under climate change, reviewing risks and opportunities from the recent past until the end of the century. To do this I developed several novel methods, which are initially used to project the future of wild and cultivated coffee cultivation in Ethiopia. For the wild species I have developed several new spatial techniques, particularly dealing with the issue of the "modifiable areal unit problem" within species extinction risk assessments. I have updated and refined existing techniques into one package, allowing multiple future climate scenarios/projections to be processed and assessed quickly.

I present my scientific findings in the form of five submitted manuscripts (see 'List of original articles', on p.8). Using the findings, results and recommendations from these papers, I repurpose the outputs and impact of the science, graphically and within various media (including two more manuscripts, media and social media), for multiple audiences.

Using these spatial techniques and visualisations, I show the impact climate change will have on Arabica coffee in Ethiopia, both as a crop and as a wild species within the humid forests of the country. I show that the present coffee-growing areas could be reduced by up to 60% if no interventions are made, but conversely, that there is an opportunity to increase the coffee growing area of Ethiopia four-fold, if the right actions are taken. For wild Arabica coffee I show that the species is threatened with extinction due to climate change. Specifically, I show that wild Arabica coffee would be assessed as Least Concern (under little or no risk; IUCN Extinction Red List) if climate change is not factored in, as opposed to Endangered (threatened with extinction) if climate change is included in an extinction risk assessment. The work in this thesis demonstrates the power of spatial analysis, modelling, and high data quality, for plant conservation.

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List of original articles

I[a1]. Davis, A.P., Gole, T.W., Baena, S., & **Moat, J.** (2012). The impact of climate change on Indigenous Arabica Coffee (*Coffea arabica*): predicting future trends and identifying priorities. *PLoS ONE*, *7*(11). https://doi.org/10.1371/journal.pone.0047981

II. **Moat, J.**, Williams, J., Baena, S., Wilkinson, T., Gole, T. W., Challa, Z. K., Demissew, S & Davis, A.P. (2017). Resilience potential of the Ethiopian coffee sector under climate change. *Nature Plants, 3(7),* 17081. https://doi.org/10.1038/nplants.2017.81

III. **Moat, J**., Williams, J., Baena, S., Wilkinson, T., Demissew, S, Challa, Z. K., Gole T.W., & Davis, A.P. (2017). Coffee Farming and Climate Change in Ethiopia: Impacts, Forecasts, Resilience and Opportunities. *Royal Botanic Gardens, Kew.* Retrieved from http://auth-kew.axis12.com/sites/default/files/Coffee Farming and Climate Change in Ethiopia.pdf

IV[a1]. Davis, A.P., Wilkinson, T., Challa, Z.K., Williams, J., Baena, S., Gole, T.W. & **Moat, J**. (2018). Coffee Atlas of Ethiopia. *Royal Botanic Gardens, Kew* (UK). Pp. 148.

V. **Moat, J**., Bachman S., Field R. and Boyd D. (2018) Refining area of occupancy to address the modifiable areal unit problem in ecology and conservation. *Conservation Biology*. Publish 23rd May 2018.

VI[a1]. **Moat, J.** (2017). rCAT: Conservation assessment tools and functions in R. *CRAN* https://cran.r-project.org/web/packages/rCAT/index.html

VII. **Moat, J.,** Gole, T. W. and Davis A. P. (2018). Least Concern to Endangered: applying climate change projections profoundly influences the extinction risk assessment for wild Arabica coffee. *Global Change Biology.* Accepted 1st May 2018.

VIII. **Moat, J.**, O'Sullivan R., Gole, T. W. and Davis A. P. (2018). Wild *Coffea arabica* conservation assessment: Endangered and threatened with extinction. In review *IUCN Red List*.

Throughout this thesis I will cite these manuscripts using the roman numerals as above.

[1] These papers are either outside the PhD period or not directly applicable for this award, they are available in Appendix I.

Publications and authors contribution

Author	Original Ideas/concepts	Experimental design	Implementation (i.e. doing the work)	Analytics	Cartography/ Visualisations	Ms. Preparations
J.M.	Ia, II, III, IVa, V, VIa, VII, VIII	Ia, II, III, IVa, V, VIa, VII, VIII	Ia, II, III, IVa, V, VIa, VII, VIII	Ia, II, III, IVa, V, VIa, VII, VIII	Ia, II, III, IVa, V, VIa, VII, VIII	Ia, II, III, IVa, V, VIa, VII, VIII
A.P.D.	Ia, II, III, IVa, VII, VIII	Ia, II, III, IVa	Ia, II, III, IVa	Ia, II, III, IVa	Ia, II, III, IVa	Ia, II, III, IVa, VII, VIII
S.B		Ia, II	Ia, II, IVa	II	II, IVa	Ia, II, III, IVa
T.W.			IVa	II, IVa	IVa	II, III, IVa
J.W.			II	II		II, III, IVa
T.W.G.						Ia, II, III, VII, VIII
Z.C.						II, III
S.D.						II, III
S.P.B.	V	V				V
R.F.						V
D.B.						V
R.O.						VIII

Table 1. Author contributions to manuscripts. See list of original articles above to look up manuscripts

J.M.: Justin Moat, A.P.D.: Aaron P. Davis, J.W.: Jenny Williams, S.B. Susana, Baena, T.W.: Timothy Wilkinson, T.W.G.: Tadesse Woldemariam Gole, Z.C.: Zeleke Challa, S.D.: Sebsebe Demissew, S.P.B.: Steve Bachman, R.F.: Richard Field, D.B.: Doreen Boyd, R.O.: Robert O'Sullivan

I have led all the work in this thesis, but as evident in the acknowledgements, this would have been impossible without the hard-work and input from my co-authors. My role has been to lead on all this work, bring the team of co-authors together, gather, archive and analyse the data, and write up the manuscripts.

List of abbreviations

AOO	Area of Occupancy
API	Application programming Interface
BCCR-BCM2.0	Bjerknes Centre for Climate Research, Bergen Climate Model, Version 2
BIOCLIM	Bioclimatic Variables (Busby, 1991)
CCAFS	Climate Change, Agriculture and Food Security
CIMP3	Coupled Model Intercomparison Project phase 3
CIMP5	Coupled Model Intercomparison Project phase 5
CSIRO-MK3.5	Centre for Australian Weather and Climate Research Mark, 3.5
DAF	Dry Afromontane Forest
DEM	Digital Elevation model
DFID	Department for International Development
EOO	Extent of Occurrence
ERDAS	Earth Resources Data Analysis System
GAM	Generalised Additive Models
GBIF	Global Biodiversity Information Facility
GBRM	Generalised Boosted Regression Models
GCM	General Circulation Models
GFDL- CM2.1	Geophysical Fluid Dynamics Laboratory, Coupled Climate Model 2.1
GFW	Global Forest Watch
GLM	Generalised Linear Models
HadCM3	Hadley Centre Coupled Model, version 3
ICO	International Coffee Organisations
IPCC	Intergovernmental Panel on Climate Change
MAF	Moist Evergreen Afromontane Forest
MARS	Multiple Adaptive Regression Splines
Maxent	Maximum Entropy models
Ms.	Manuscript
RCP	Representative Concentration Pathway
SCIP	Strategic Climate Institutions Programme
SDM	Species Distribution Models
TRF	Transitional Rain Forest
TSS	True Skills Statistics
UTM	Universal Transverse Mercator
WCRP	World Climate Research Programme

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The research contained in this thesis was partially financed by the Strategic Climate Institutions Programme (SCIP) in Ethiopia. The PhD was supported by the Royal Botanic Gardens, Kew (RBG, Kew). I am extremely grateful for the opportunity that I have been given by the SCIP programme and RBG Kew.

As can be seen from the lengthy list of co-authors, this has not been a solo effort, and indeed could not have been. I am hugely grateful for their support, insight and expertise. To Jenny Williams for her expertise with data processing as well as collecting field data in Ethiopia. Susana Baena, for her expert skills in remote sensing. Timothy Wilkinson for staying the course with the *Coffee Atlas of Ethiopia* and for his cartographic knowledge par excellence, as well as for gathering field data in Ethiopia. To Steve Bachman for his 'artistry' with the IUCN Red List and criteria and continued support throughout. Oliver Whaley, whose patience and encouragement have been generously given and gratefully received and for reminding me of the 'real world'; and yes, I will be working on Peru next. Robert O'Sullivan, for kicking off the original Arabica coffee assessment many years ago. To our Ethiopian collaborators, Tadesse Woldemariam Gole, Zeleke K. Challa and Sebsebe Demissew, I am immensely grateful for your support, knowledge and insight; the findings within these manuscripts and thesis would not exist without you all.

I am thankful to all the coffee farmers and coffee farming communities across Ethiopia for their participation in this work, and their hospitality and assistance during field work. You are the custodians of the future of Arabica coffee, my hope is that some of this work will have a positive impact on your lives.

I am grateful to both my supervisors; Doreen Boyd and Richard Field at Nottingham University's, School of Geography for firstly taking me on as an 'unconventional' student and PhD candidate, and then for their time, support and continual editing and reviewing of manuscripts.

I would like to give a very belated appreciation to David Du Puy and Paul Bygrave who took a gamble on me so many years ago (on the Madagascar project) and set me on path with plants and spatial analysis (GIS as it was then) – thank you both so much.

To my great friend and academic partner, Aaron Davis, co-author and supervisor, for his continued patience with my long-winded explanations, sticking with the science, even

after well over a year of review and over five resubmissions. His endless knowledge of all things coffee (all species, not just Arabica) brings a reality to what could have been very abstract modelling and algorithms. I think the debt is well and truly paid for when I helped with his PhD over twenty years ago!

Finally, and most importantly, to my children, Amelie and Aaron for their continuing support and reality checks, and to my fantastic wife Alison, for her constant encouragement and reading and correcting my esoteric English. I would have given up a long time ago if it wasn't for you.



*Figure 2. A coloured engraving of Arabica coffee (*Coffea arabica*) from the book "An historic Account of Coffee" by John Ellis (1774). Image: RBG Kew.*

Introduction

1. Aims

We are faced with a rapidly changing world with elevated levels of deforestation, climate change, population growth, and humans' continued exploitation of the natural environment (Vitousek *et al.*, 1997; Dirzo and Raven, 2003; Dale and Fortin, 2014). These changes to the environment are predicted to have major impacts on the natural capital of the world and the majority of our crop species (Fischer *et al.*, 2005). *Coffea arabica* (Arabica coffee) is an important case study, being the most important crop in Ethiopia and one of the world's most traded commodities (Sivarajan, Biju and Mathew, 1992; Davis *et al.*, 2012; International Coffee Organization (ICO), 2016). Its future status has been shown by many to be highly affected by climate (Dudu 2012; Haggar & Schepp 2011; Jaramillo et al. 2011; Laderach et al. 2011; Campa et al. 2012; Bunn et al. 2015). Using *Coffea arabica*, this thesis demonstrates how advances in computing power, analytical techniques and the rise of easily available spatial data (both for plants and associated data, e.g. satellite imagery and climate data) increasingly allows us to tackle the complex interactions between environmental change and human activity.

The ultimate objective of this thesis is to forecast the fate of wild and cultivated Arabica coffee within its homeland, in this changing world, whilst identifying the needs, methods and challenges in doing this type of analysis. Within this thesis I forecast this fate for wild and cultivated coffee, both spatially across the landscape and quantify the extinction risk of the wild species. I address the inherent limitations, opportunities and interventions needed. I endeavour to make the results and findings accessible and digestible to multiple different audiences, as the global population is the stakeholder in the future of coffee. Finally, this thesis explores the opportunities provided by these methodologies, visualisations, and results, for the future of coffee in Ethiopia.



Figure 3. Coffeehouse at Tophane, Constantinople. From "Voyage pittoresque de Constantinople et des rives du Bosphore" Antoine Ignace Melling Strasbourg Treuttel et Würtz (Paris, 1819). Image: Jean-Pierre Dalbéra, Wikimedia.

Coffee played an important role in the social life in the Ottoman Empire. It was not until the 17th century that coffee as a drink spread to Europe.

2. Global overview

The latest reports on the global state of biodiversity paint a worrying forecast for the state of the planet; threats are intensifying and biodiversity loss is predicted to continue apace (Visconti *et al.*, 2016), despite attempts to reverse these trends (Hoffmann *et al.*, 2010). It has been calculated that 21% of all plants are currently threatened with extinction (Brummitt *et al.*, 2015), yet nearly all life on Earth is dependent on plants. At the simplest level, plants provide us with food, shelter, medicines, climate regulation and the air we breathe (Wood and Habgood, 2010).

Against a backdrop of a changing climate, there is a critical need to understand the responses of the world's plants to their changing environment (Royal Botanic Gardens Kew, 2016a). The symptoms of climate change on the planet's plants will be revealed in three possible outcomes: extinction, migration or *in situ* adaptation (Aitken *et al.*, 2008; Dawson *et al.*, 2011; Royal Botanic Gardens Kew, 2016a).

There are numerous studies that show that food security and the fates of the world's crops under climate and socio-economic change will be greatly challenged (Fischer *et al.*, 2005). Nearly all indicate that the impacts of climate change will be significant, but with a wide range of predicted impacts (e.g. between 5 million and 170 million people at risk of hunger by 2080 (Schmidhuber and Tubiello, 2007)), and that this strongly depends on the socio-economic development of the region (Schmidhuber and Tubiello, 2007). It has also been shown that wild crop relatives (CWRs), which are an important source of genetic diversity for crop adaptation, are highly threatened under a changing climate (Jarvis, Lane and Hijmans, 2008). *Coffea arabica* is an ideal crop to study for its fate under climate change, being both a CWR and crop species. It is also endemic to some of the world's poorest developing nations. Coffee is familiar to nearly everyone, as one of the world's most widely consumed beverages, and invokes a great deal of passion in many people. With such familiarity, coffee can be used as a flagship species to connect the general public and the commercial sector to plant conservation and climate change.

3. Arabica coffee and climate change

For hundreds, if not thousands, of years, coffee growing has been practised in Ethiopia using Arabica coffee (*Coffea arabica*) (Davis *et al.*, 2012). The early use of coffee was restricted to gathering fruits from wild forests, with semi-domestication probably coming soon afterwards.

Coffee is the backbone of Ethiopia's economy, providing more than 30% of the country's export earnings, totaling between $500–$800 million in 2014 (Minten *et al.*, 2014). It is estimated that 25% of the population depend directly or indirectly on coffee for its livelihood (Hein and Gatzweiler, 2006). Ethiopia's Poverty Reduction Strategy Paper and Growth and Transformation Plan (2010/11 to 2014/15) highlights that increasing coffee productivity, while conserving biodiversity and genetic resources, will play a vital role in Ethiopia reaching Millennium Development Goal 1 (eradicate extreme poverty and hunger). However, coffee production in Ethiopia faces numerous challenges in an uncertain climatic future.

Recorded climate data from the 1960s onwards show an average increase in the mean annual temperature for Ethiopia of 0.28 °C per decade (Jury and Funk, 2013), a shortening wet season, and an increase in the number of hot days (UNDP Climate Change Country Profile for Ethiopia). Our initial modelling (Davis et al. 2012 [manuscript I[a]]) indicated a negative impact (due in the main to increasing temperature) on wild coffee forests (and hence coffee production in Ethiopia), but also that there are opportunities for climate resilience. Thus, Arabica coffee is the target species for this thesis, being by far the most important commodity crop species in Ethiopia. In addition, Ethiopia is the source of perhaps more than 95% of the world's genetic diversity for this globally important economic species (Davis *et al.*, 2012).

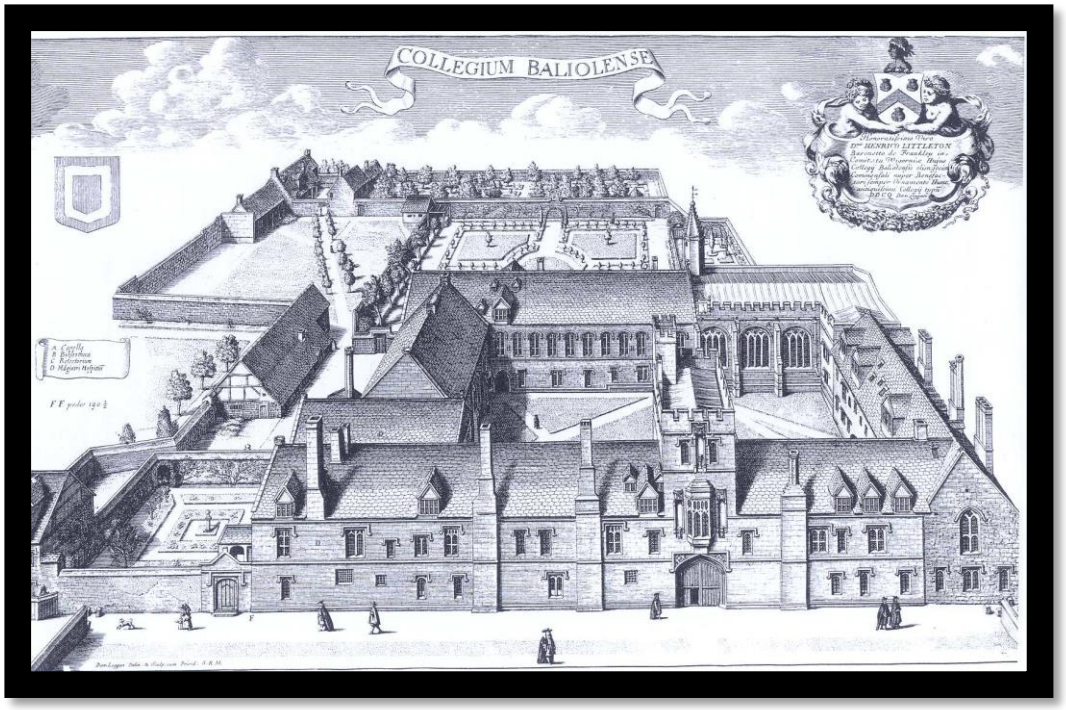


Figure 4. Balliol College Oxford (1675). Image: public domain, Balliol archives.

Evelyn's diary of 1637 refers to members of the college taking coffee, which is the first record of the drink being enjoyed in England.

4. Identifying the knowledge gaps

I have been working in plant conservation and spatial analysis for many years, producing spatial algorithms for conservation assessments and applying remote sensing to produce habitat and vegetation maps. My interest in Arabica coffee started with a simple observation in Ethiopia: that coffee farmers were having difficulties with coffee production, against a backdrop of ever-increasing temperatures and declining rainfall. My colleagues and I assessed this within paper I[a], where we used data from herbarium specimens collated over many years, and existing wild specimen coffee data, to see if there was a climate signal and if this would be affected by climate change.

Previous studies on coffee and climate change have looked at the crop species globally (Haggar and Schepp, 2011; Ridley 2011), with little or no attention to wild species distributions (the wild species has much higher genetic and physiological variability compared with the cultivated Arabica coffee (Adugna *et al.*, 2005; Dessalegn, Herselman and Labuschagne 2008)). Those studies mostly do not consider possible interventions (irrigation, soil treatments etc.) within their analyses. Most analyses are also at a spatially crude scale (10–50 km grain), only considering one or a few climate models or scenarios, and without thought given to the habitat (humid forest) in which wild coffee grows. None of these studies look at the interventions needed to quantify or ameliorate the possible effects of climate change on coffee production. To protect the future of coffee growing, we need to understand the extinction threat for wild coffee (under an IUCN conservation assessment (IUCN, 2012)), including the influence of climate change. Finally, the results and findings of my thesis need to be understandable to multiple stakeholders if we wish to influence the future fate of coffee in Ethiopia and perhaps worldwide.

5. Research objectives

The primary outcomes of this PhD are to forecast the fate of wild and cultivated coffee in Ethiopia under climate change, reviewing the risks, opportunities and resilience potential, over the course of this century. To achieve this, I have set following research objectives:

The specific objectives are to:

1. **Understand the environmental conditions for wild and cultivated coffee in Ethiopia:** reviewing and mapping coffee to identify the environmental suitability and threats (including deforestation and land-use).
2. **Understand cultivated and wild coffee in Ethiopia under a changing climate:** understanding the influence of climate change on the specific climatic space in Ethiopia under scenarios of climate and interventions.
3. **Quantify the impact of climate change on coffee in Ethiopia and identify resilience**: using species distribution modelling and climate change projections to understand the impacts of climate change on the distribution of wild and cultivated coffee.
4. **Quantify the extinction risk and conservation status for wild Coffee in Ethiopia**: develop spatial algorithms and generation-length models to assess the extinction risk to wild Arabica coffee.
5. **Communicate the results:** communicating the potential impacts of climate change on coffee, visualising uncertainties and reviewing management implications to a wider audience (from farmers to governments, and to the general public).

Within this thesis I provide a narrative, from inception (see appendix IV for the research timeline) to desktop study (Paper I[a]), moving on to the full project and deliverables (papers III, IV and V), arriving at a climate resilient strategy for the Ethiopian coffee sector and finally arriving at an extinction risk assessment (papers VII and VIII) for *C. arabica* (Figure 5). All my findings and conclusions are driven by the analyses of plant distribution. In the main I use species distribution models (SDMs), climate change models, and the forested area (derived from Landsat imagery) to

forecast species extent and quality, through space and time. I also apply fundamental spatial analysis (Papers V and VI) to demonstrate how differences in baseline data measurements (points and cells) affect commonly used conservation metrics (Area of Extent (AOO)). Finally, I apply the findings from this point/cell analysis to the outputs from my climate change forecasts to give a species extinction risk assessment for *C. arabica* (manuscripts VII and VIII).

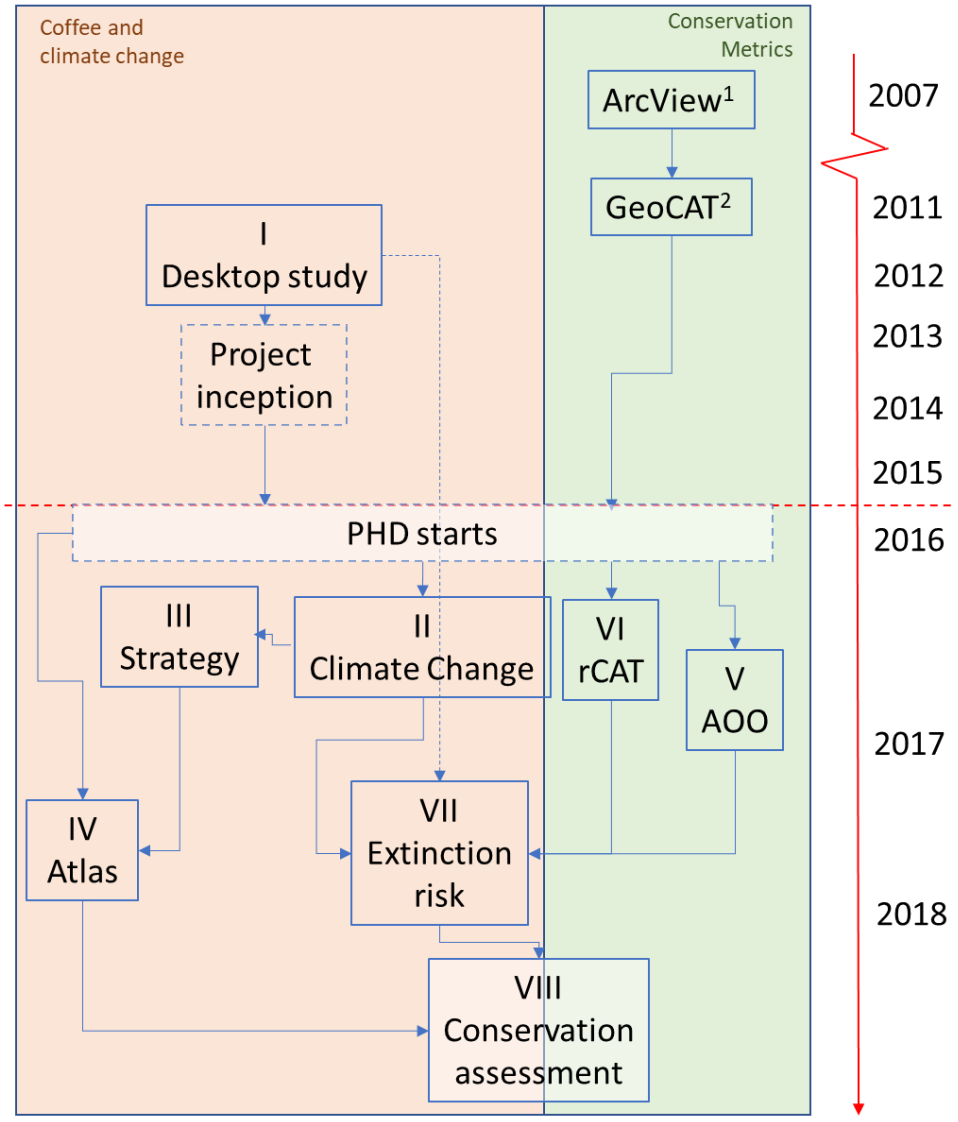


Figure 5. Major thesis work flow, manuscripts and time lines.

[1] (Willis, Moat and Paton, 2003; Moat, 2007) [2] (Bachman *et al.*, 2011; Moat, Vizzuality and Bachman, 2017)



Figure 6. Interior of a London coffee house 1668 (Image: public domain, Wikimedia). From Pim Reinders, Thera Wijsenbeek et al., Koffie in Nederland: Viereeuwen culturgeschiendenis, (Zutphen: Walberg Pers; Deft: Gemeente Musea Delft, 1994).

6. Environmental requirements of *Coffea arabica*

Arabica coffee (*Coffea arabica*) and robusta coffee (*Coffea canephora*) are the main species used in the production of coffee, although *C. arabica* is by far the most significant, providing approximately 60% of commercial production (International Coffee Organization (ICO), 2016). Within this thesis I only deal with *C. arabica*. I mainly refer to this species by its common name (Arabica coffee).

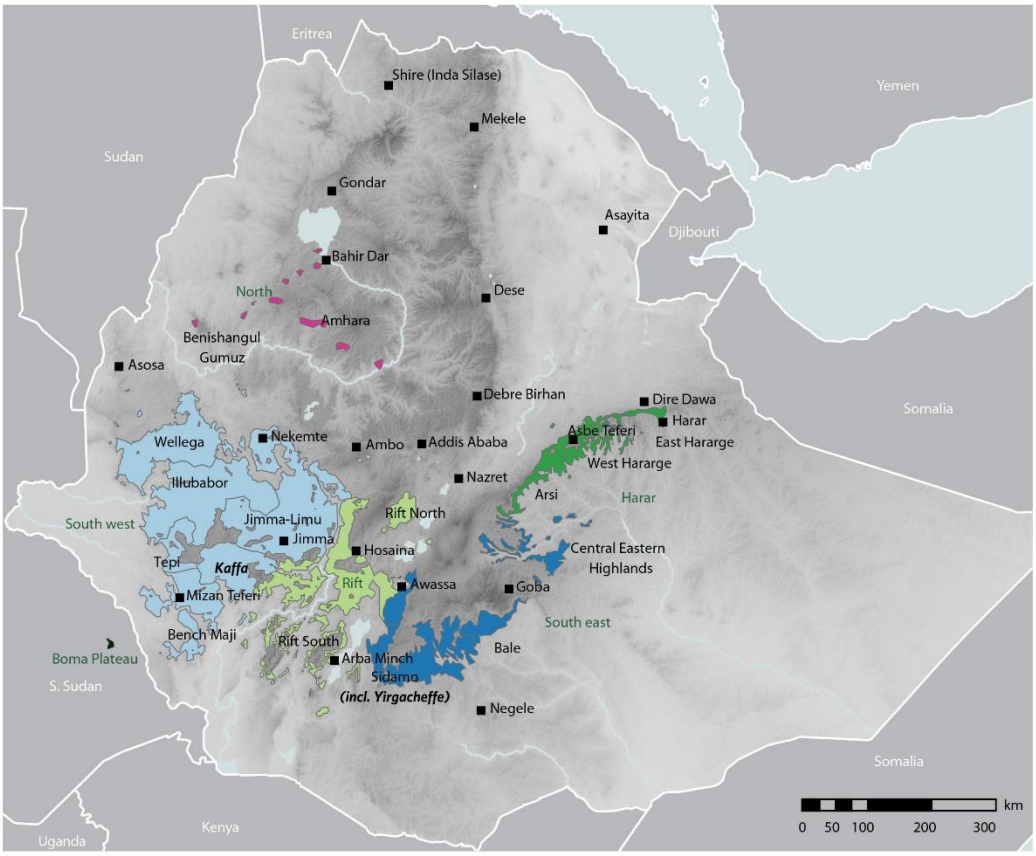


Figure 7. The main coffee growing zones and areas of Ethiopia and South Sudan.

The coffee zones represented by coloured polygons: red/pink, North Zone (coffee areas: Amhara and Benishangul Gumuz); light blue, South West Zone (coffee areas: Wellega, Illubabor, Jimma-Limu, Kaffa, Tepi and Bench Maji); light green, Rift Zone (coffee areas: Rift North and Rift South); dark blue, South East Zone (coffee areas: Sidamo, Yirgacheffe, Bale and Central Eastern Highlands); dark green, Harar Zone (coffee areas: Arsi, West Hararge and East Hararge); black, Boma Plateau, South Sudan. [Adapted from papers II and III]

Coffea arabica grows wild in the forested highlands of south and south-western Ethiopia (Figure 5), with a small population in South Sudan in the Boma plateau, which borders Ethiopia (Davis *et al.*, 2012). It grows as a small, rather short-lived tree (reaching a height of 7m and up to 3m spread) in moist evergreen forest, at altitudes of 950 to 1950m, although it should be noted that a lower altitude limit of 1200m is more realistic today, due to deforestation and perhaps climate change (paper VI). Following the terminology of Friis et al. (2010), wild coffee occurs in Moist Evergreen Afromontane Forest (MAF), and Transitional Rain Forest (TRF). Cultivated Arabica coffee is mainly grown in Moist Evergreen Afromontane Forest (MAF), and Transitional Rain Forest (TRF), but in some locations (Harar region, Amhara region, and highland areas in the south-west above 2000 m), it is cultivated in the wetter areas and at higher elevations, in evergreen forest (Dry Evergreen Afromontane Forest and Grassland Complex (DAF)).

Coffea arabica, enjoys subtropical (cool tropical), almost temperate regions, that do not suffer frost or strong winds, that have well distributed rainfall and a defined dry season lasting 4–5 months. The species prefers a deep, well-drained, loamy soil, which is slightly acidic (pH 5.8–6.0 being the limit for good root growth), rich in humus and exchangeable bases (alkali and alkaline earth metals, principally calcium, magnesium, potassium and sodium). Soil moisture and oxygen are required throughout the rooting depth. The optimum temperature range for *C. arabica* is 18–23°C; temperatures over 30°C can be harmful to growth, flowering and seeding (Coste, 1992).

The climatic requirements for the species can at a simple level be viewed as an interaction between temperature and precipitation (paper II). Areas with low rainfall cannot endure increases in temperatures, whereas areas with high rainfall can. There are nuances to this simplification (for example seasonality is also very important), but this simplification holds for the majority of the species' range (see paper II).



Figure 8. Tom King's Coffee House, Covent Garden market (Image: public domain Wikimedia).

Tom King's coffee house is an open-fronted lean-to shed on east wall of the Church in Covent Garden market. From Hogarth's – Morning from Four Times of the Day (1736).

7. Methods

Overview

The outcomes of climate change on the world's plants will be revealed in three possible outcomes: extinction, migration or *in situ* adaptation (Aitken *et al.*, 2008; Dawson *et al.*, 2011; Royal Botanic Gardens Kew, 2016a).

Within this thesis I deal with the first of these two: extinction and migration. I have used multiple methods and techniques and they are detailed within each paper. Here I present an overview and examine some of the issues and biases that need to be considered when working with SDMs and climate projections, as well as the methods we have used to ameliorate or consider them. Again, these are detailed within the individual papers.

SDM modelling methods

I used numerous modelling methods within our SDMs for the present day and the future. The details of these methods are in papers I[a] and II and the supplementary material for paper II (https://tinyurl.com/Moat-2017-nature-plants-sup). Within this chapter I present an overview of the methods, biases and issues and how I strived to reduce and account for these issues within the modelling and interpretation of the results. Within the SDMs and extinction risk assessment, I considered many variables and metrics, which are summarised in Table 2.

Variable	Description	Variables used	Papers (No. of variables used)
Time	Time periods for future and past climates	2000, 2020, 2050, 2080 1960-1990, 2010-2039, 2040-2069, 2070-2099	I[a] (4) II (4)
Climate change emission scenarios (CMIP3) or Representative Concentration Pathways (RCP)	Scenarios under CMIP3 (Pathways) for the emission of greenhouse gases	A1B, A2A, B2A, RCP8.5 (reviewed in comparison to A2)	I[a] (3) II (2/3)
General circulation models	Climate models produced by multiple institutions around the world	Reviewed: 23 GCM Used: HadCM3 BCCR-BCM2.0 CSIRO-MK3.5 GFDL- CM2.1	I[a] (1) II (23/3)
Migration scenarios	Scenarios of species movement, ranging from full	A, B, C, D, E & F	I[a] (1) II (6)

	migration (with assistance) to no movement.		VII (3 forest only)
Bioclimatic Variations (BIOCLIM)	A set of 19 raster data sets that represent annual climate trends, i.e. rainfall, temperature and seasonality.	See (Moat *et al.*, 2017) for details	I[a] (19) II (19/9)
Bio-Climate Domains	The major climatic domains a species exists within.	East & West of the rift valley	I[a] (1) II (2)
SDM algorithms	The actual methods for the SDM modelling.	Generalised Linear Models (GLM), Generalised Boosted Regression Models (GBRM), Generalised Additive Models (GAM), Multiple Adaptive Regression Splines (MARS), Random Forest (RF), Maximum Entropy (Maxent), Ensemble	I[a] (1) II (7)
Spatial Conservation metrics	Metrics used to describe species range, area and population numbers.	Area, AOO, EOO & population size (normal or linear demographics)	I[a] (1) II (1) VII (4)

Table 2. SDM variables and metrics used in this study.

N.B. Where number of variables used, the first number is the number reviewed and the second is the number used in the SDMs.

There is abundant literature regarding the use or misuse of SDMs (see next sections and paper II for details). Despite the assumptions and uncertainties, future projections using SDMs and GCMs are extremely powerful, if used correctly and validated by ground-truthing. On the use of niche models (SDMs) for climate change analyses, Wiens et al. (2009) conclude by stating: 'Viewed at appropriate scales, the output of current SDMs can provide glimpses of probable futures that can be useful in conservation and resource management. The alternative is to ignore the future, which is really not an option.' Below I show how I have tackled, reduced and demonstrated these assumptions, biases and issues.

Comparison of modelling complexity

In Paper I[a] the analysis was limited; using four-time periods, one GCM, three emission scenarios, one migration scenario and treating the species as one bioclimatic domain. This approach produced nine models, which was enough to demonstrate that the species has a climatic signal, with a likely climate change effect. I used this knowledge in

Paper II but needed to be as robust and inclusive as possible. Within Paper II, I used: four-time periods, three GCMs (after reviewing all 23 GCMs), two emission scenarios (also reviewing RCP8.5), six migration scenarios, two bioclimatic domains and seven SDM methods, which produced over 2000 models. This demonstrated that the study in Paper II was much more rigorous than the first paper (II) with orders of magnitude (x 225) of increased complexity.

Fundamental vs. realised niche

There is much debate about the niche represented by an SDM, chiefly around realised niche versus fundamental niche. The niche refers to the environmental condition and position of a species in an ecosystem. The fundamental niche is where the species can exist (without species interactions such as competition), whereas the realised niche is the niche the species exists within (with species interactions). Most studies using SDMs identify the realised niche (Franklin, 2010); the closer the realised niche approaches the fundamental niche the better any SDM projections and results are likely to be. Using bioclimatic variables, the results tend to approach the fundamental niche, especially when being projected to new areas (i.e. introduced ranges) or future climates (Jiménez-Valverde, Lobo and Hortal, 2008; Franklin, 2010). In paper II, the niche-only scenarios (migration scenarios A, B and E), combined with comprehensive ground truthing, showed that our SDMs were very close to the fundamental niche: that is, where Arabica coffee grows wild and is farmed. The niche and forest migration scenarios (C, D and F, paper II) that were used conserve the association to the fundamental niche, but by applying the coffee forest as a mask means that we can get closer to the realised niche.

Representing uncertainty

Predicting the future climate with high certainty is impossible, but by using multiple climate models and assuming certain pathways of greenhouse gas emissions, it is possible to make future projections. Our field work verified that areas predicted to be climatically poor were either partially suitable or unsuitable for coffee cultivation, with either no or low coffee yields/harvest (See Paper II and appendix V). Despite the many uncertainties, future climate models can deliver useful approximations of future conditions (Wiens *et al.*, 2009), which can be used to give insights into the sensitivity of coffee production (and the species in the

wild) to a changing climate. I compared different climate models and also explored reasons for the projected change in the coffee farming suitability niche (Paper II), which gave us insights into the vulnerabilities of coffee growing, at least in terms of exposure (Dawson *et al.*, 2011; Foden and Young, 2016).

Also, we can assess the levels of confidence (uncertainty/variation) in our projections. To represent these uncertainties (in our case GCM variation) I displayed the area results (bar charts) with error bars (Paper II). For the scientific papers I adopted the same symbology for maps as used in the widely read IPCC report (IPCC, 2013). Within the more public-friendly strategy report (Paper III), I used line thickness to denote the variation (we also used the term "agreement" instead of "variation") (Figure 9).

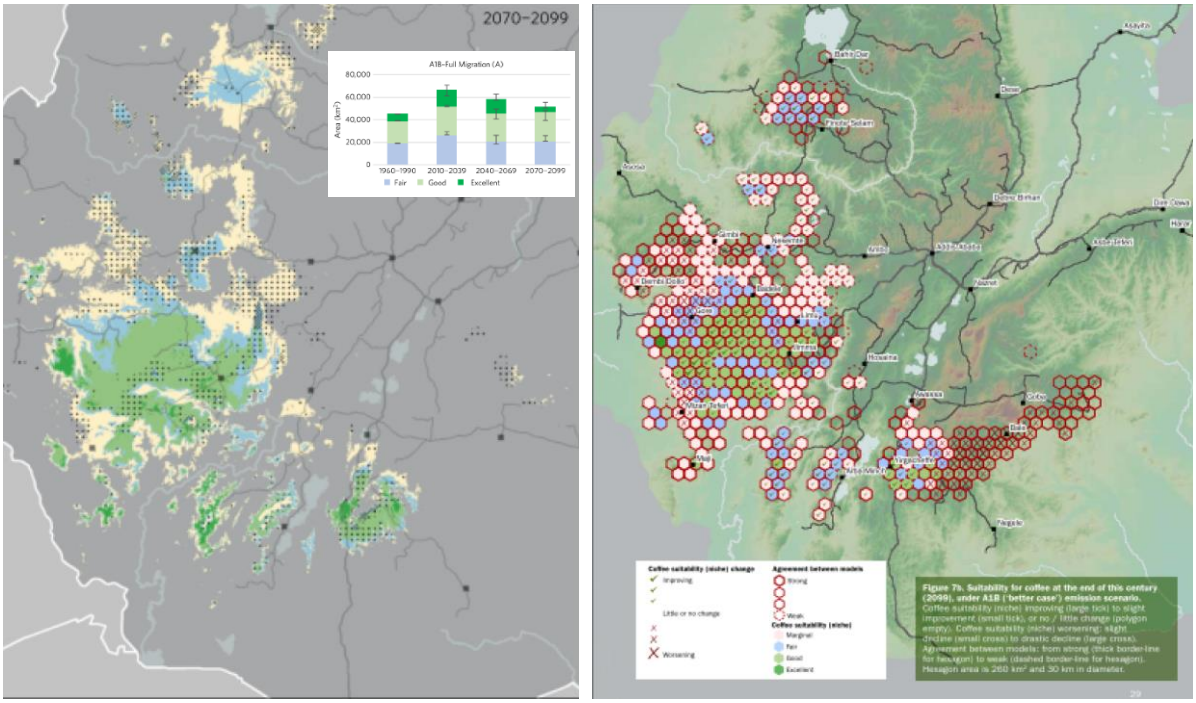


Figure 9. Different graphical representation of GCM uncertainly within papers II and III.

Left for science audience; right for a general audience.

Working environment (software)

To manipulate and effectively work with the many different data sources and types, I needed to use multiple packages and environments. Below is the list of main packages and environments used (Table 3).

Package	Use	Citation	Papers
ESRI ArcGIS	Visualisation and cartographic products. Simple map maths and spatial data manipulation	(Esri, 2014)	I[a], II, III, IVa & VII
Locus Pro	To display maps (model and forest data) on android phones in the field and for collection of data	(Asamm Software, 2017)	II
ERDAS Imagine 2013	Satellite imagery manipulation and processing	(ERDAS Imagine® software 2013)	II, II & IVa
ENVI	Satellite imagery manipulation and processing	ENVI version 4.8 (Exelis Visual Information Solutions, Boulder, Colorado)	II, II & IVa
R	Core simulation and programming environment	(R Core Team, 2016)	II, IVa, V, VI[a] & VII
R package Biomod2	SDM modelling and climate change predictions	(Thuiller, Georges and Engler, 2014)	II & IVa
Maxent	SDM modelling and climate change predictions	(Phillips and Dudik, 2008)	I[a] (II & IV[a] within BIOMOD2)
R package Rgdal	Manipulation of spatial data map projections	(Bivand, Keitt and Rowlingson, 2016)	VIa & V
R package raster	Manipulation of raster imagery in R	(Hijmans, 2016)	VII
R package sp	Manipulation of spatial data in R	(Bivand, Pebesma and Gomez-Rubio, 2013)	II, VI[a] & VII
R package lattice	Producing hexagons for AOO calculations	(Sarkar, 2008)	V

Table 3. Software, packages and programming environments used in this thesis

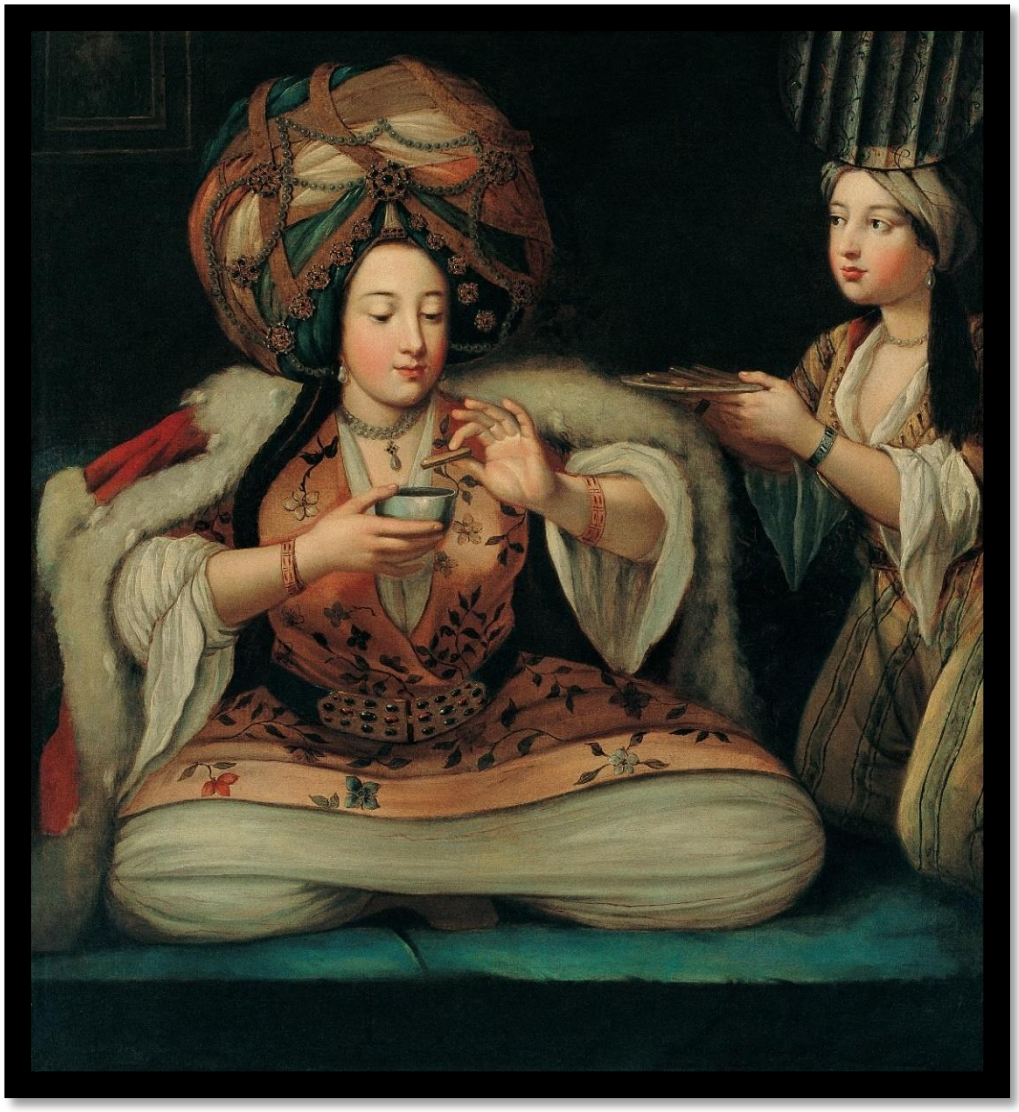


Figure 10. French school of painting – Enjoying coffee (Pera Museum, Image: Wikimedia).

8. Data

Field work data and ground control data

I used a large amount of ground-truthed data to produce the SDM models, and for much of the analysis. These data were derived from multiple sources and are summarised in Table 4; Figure 11 show the main data flow for the coffee analyses used within this PhD.

In addition to the coffee ground-truthing data, I also used further datasets to test the two methodologies and tools papers (V and VI[a]). I used legume data from Madagascar (Du Puy and Moat, 2002; Du Puy *et al.*, 2002; Labat and Moat, 2003), *Coffea* (all species) data from Africa (Davis *et al.*, 2006), and finally species of conservation concern from the Caribbean (Burton, 2008; Royal Botanic Gardens Kew, 2016b).

Paper	Summary and source of ground data
I[a]	751 data points • Field survey data for populations in Ethiopia (648 data points; data collected 2000–2006, (T. Gole, unpubl. data) • Records of wild populations from literature (18 data points; from 1941 (Thomas A.S., 1942) and 1964/5 (Meyer, 1965) • Herbarium specimens (14 data points; collections made 1941–1984). Herbarium specimens were surveyed at the Natural History Museum, London (BM), Royal Botanic Gardens, Kew (K), the Museum of Natural History, Paris (P), and the herbarium of the Wageningen branch of the National Herbarium of the Netherlands (WA)
II, III & IVa	3,070 data points • 1624 were coffee presence data points and 1446 non-coffee points • Coffee presence data, comprised of 824 historical (1941–2001 mainly from paper I[a]) and 800 contemporary (collected over 2013–2016) points (with coffee production type, forest cover and condition, and global positioning system (GPS) data recorded).
V	22,848 data points • Legumes of Madagascar. 19,343 georeferenced records for 761 taxa (Du Puy and Moat, 2002; Du Puy *et al.*, 2002; Labat and Moat, 2003) • *Coffea* species of Africa. 2,606 records for 58 taxa (Davis *et al.*, 2006) • Selected Caribbean endemics. 899 records from 10 taxa (Burton, 2008)
VI[a]	19,343 data points • Legumes of Madagascar. 19,343 georeferenced records for 761 taxa (Du Puy and Moat, 2002; Du Puy *et al.*, 2002; Labat and Moat, 2003)
VII & VIII	1,649 data points • 1624 data points for coffee presence in Ethiopia (from paper II) • 25 data points for coffee presence in for South Sudan (from paper I)

Table 4. Summary and sources of ground control (point) data

Other data

To represent the real world as information, which can be manipulated by computer and ultimately numerate our findings, we need to produce spatial data which can be organised and managed (Harder, Ormsby and Balstrøm, 2013). There are two main approaches to represent geographic data: the discrete object view and continuous surface view of the world (Harder, Ormsby and Balstrøm, 2013). With ever-increasing access to open geographic data, there are many datasets that can be utilised to model and quantify the natural environment. The data used within this thesis are from multiple sources, from multiple time periods, in multiple formats and represent many different data types. In Table 5 (below) I list the main data sources used and their data type. Numerous other data sets have been used in the visualisations (i.e. roads, place names, country boundaries, etc.), but these were not used for the principal analysis:

	Point data	**Polygon data**	**Raster (continuous data)**	**Source**	**Manuscripts**
Specimens and observations	Database of observations with latitude and longitude	Country occurrence data		Field work (> 30 field expeditions within Ethiopia; one in South Sudan; 2009 to 2017) observations, Herbarium specimens (Davis *et al.*, 2012). World checklist (Royal Botanic Gardens Kew, 2017)	I[a], II, IVa, V, VI[a], VII & VIII
Climatic data	Individual climate station data		Raster files at 1 km^2 resolution	(Busby, 1991; Ramirez and Jarvis, 2008)	I[a], II, III, IV[a], VII & VIII
Satellite imagery			Raster files at 30m resolution	From Landsat (United States Geological Survey, 2015) and derived products GFW (Hansen *et al.*, 2013)	II, III, IV[a] & VIII
Protected areas		Protected planet shapefiles		(IUCN & UNEP-WCMC, 2016)	I[a], II, IVa & VIII
Elevation data			DEM at 90m resolution	(Jarvis, A. *et al.*, 2008)	II & IV[a]

Table 5. Principal data set used

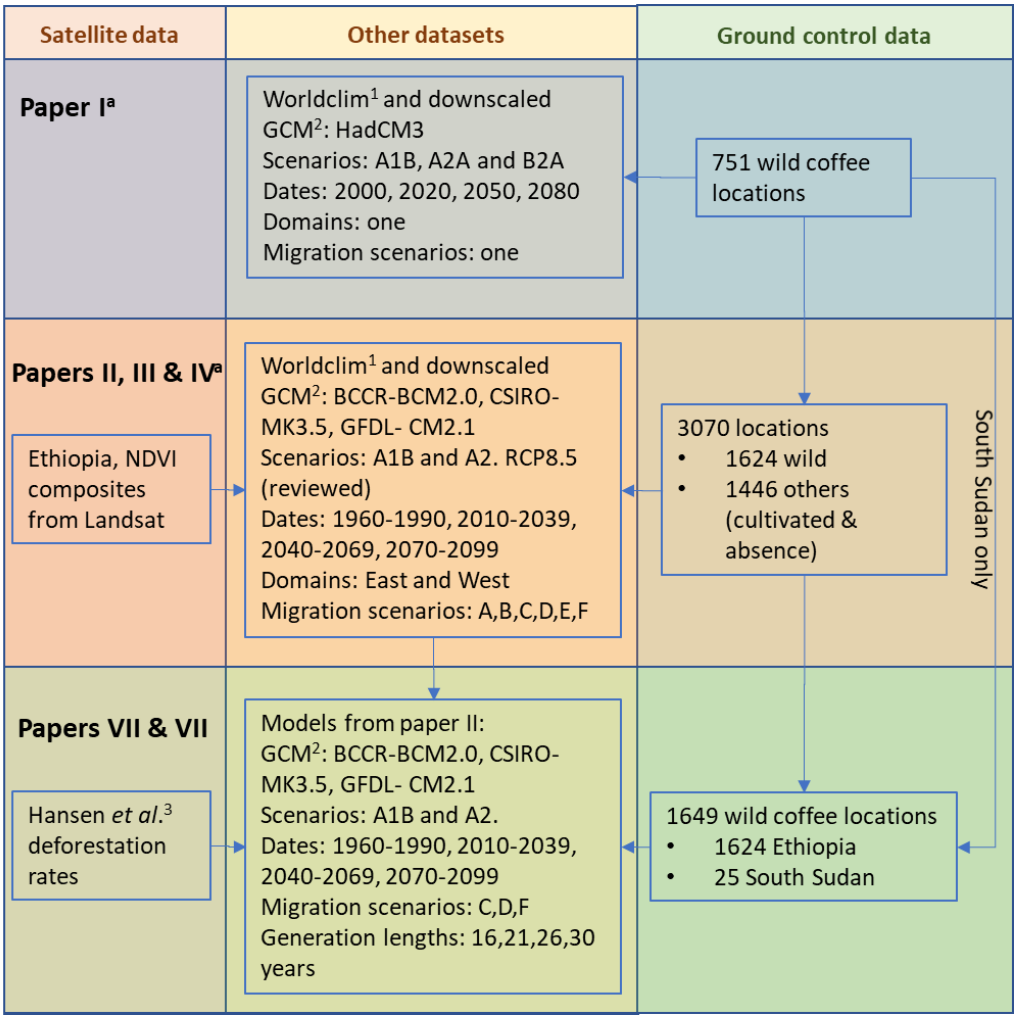


Figure 11 Summary diagram of datasets and data flow used in the main coffee papers and analysis.

[1] (Busby, 1991), [2] (Ramirez-Villegas and Jarvis, 2010), [3] (Hansen *et al.*, 2013)



*Figure 12. Arabica (left) and Liberica (*Coffea liberica*) coffee growing in Ceylon (Sri Lanka), 1869. (Image: RBG Kew)*

The Arabica coffee crop of Sri Lanka was all but destroyed within a decade by an outbreak of coffee leaf rust, which devastated the human population (the island was evacuated) and perhaps led to the English drinking more tea (Cruwell, 1878).

9. Outputs

The five manuscripts in Section 10 are the main science outputs from this PhD. In this section, I review these papers in terms of media types, showing how they were used to communicate with different audiences.

Communicating the science

Communicating science to different audiences is not straightforward; one size certainly does not fit all. Scientific papers are generally read by our peers, and peers only, whilst most of the public get their information about science from other media (Ipsos MORI Public Attitudes to Science 2014). If you want to make a difference or motivate your audience, you have to engage with the media (Science Media Centre, 2017). Bultitude (2011) and Osborne (2000) provide a list of key motivations/arguments for science communication:

- **The utilitarian argument** – The people involved will gain technical skills and knowledge that will be useful to them in their wider lives.
- **The economic argument** – Advanced societies require a technologically skilled workforce; science adds significantly to the overall output of a country (or region).
- **The cultural argument** – Science represents a 'shared heritage' and should be recognised as a wider part of our culture.
- **The democratic argument** – Science affects most major decisions in society. Therefore, it is important that the public can interpret basic scientific information.

There are many classification schemes for the type of audience, ranging from educational and social levels to how information/news is consumed. Here I use the simplest set of three classes: the lay, managerial and the expert audience (Muraski, 2013; Reid, Kiefer and Kowalski, 2013) (Table 6).

Audience Type	**Description** (Reid, Kiefer and Kowalski, 2013)	**Papers**	**Other media**
Lay	The "lay" audience has no special or expert knowledge. They tend to connect with the human-interest aspect of articles. They usually need background information; they expect more	Secondary: III &VII	Print, Broadcast, Internet

	definition and description; and they may want attractive graphics or visuals.		
Managerial	The "managerial" audience may or may not have more knowledge than the "lay" audience about the subject, but they need knowledge, so they can make a decision about the issue. Any background information, facts or statistics needed to make a decision should be highlighted.	**Primary: III, IV^{a} & VIII** Secondary: I^{a}, II & VII	Print, Broadcast, Internet
Expert	The "experts" may be the most demanding audience in terms of knowledge, presentation, and graphics or visuals. Experts are often "theorists" or "practitioners". For the "expert" audience, document formats are often elaborate and technical, style and vocabulary may be specialised or technical, source citations are reliable and up-to-date, and documentation is accurate.	**Primary: I^{a}, II, V, VI^{a} & VII** Secondary: III, IV^{a} & VIII	Print, Broadcast, Internet

Table 6. Audience types (Reid, Kiefer and Kowalski, 2013)*, papers and media.*

The audience will have diverse levels of expectation from the science they are presented with. Pure papers on methods for conservation metrics (papers V & VI), will have a very limited audience and we would not expect the audience to extend beyond the expert. With coffee, you immediately have a hook across all audiences, but again you would not expect the lay audience to digest a peer reviewed paper (although with the open access of papers this is increasing). Within my coffee research I present our findings to multiple audiences (Table 7), targeting audiences and stakeholders that can make a difference.

Specific audience	**Main communication types**	**Motivation/Argument[1]**
Scientist and experts (**Expert**)	Papers: I^{a}, II, V, VI^{a} & VII	• Utilitarian [Peer review and quality control]
In-country famers, coffee workers and producers (**Lay**)	Papers: III & IV^{a}, print, broadcast and internet	• Utilitarian • Economic • Cultural
Policy and decision makers (**Managerial and expert)**	Paper III & IV^{a}, print, broadcast and internet	• Democratic
The general public (**Lay**)	Print, broadcast and internet	• Cultural • Democratic [Awareness]

Table 7. Specific audience and motivation for communications. N.B. see Table 6 for audience types in brackets.

[1] (Osborne, 2000)

Presentation of information

With each audience type, I needed to use different graphics, cartography and data visualisations to convey the messages and data. However, one needs to also consider the myriad levels of the readership; education, awareness and sensing (i.e. though different media and different senses).

Visual media

Spatial data obviously lends itself to presentation as maps and cartographic outputs, but the presentation of maps is not a straightforward process; consideration is needed with: scale (see appendix VI), map projection, colours, symbols and output types.

Colours & symbolisation for printed media

Within most of the publications, the cartographic output was relatively simple with only a few classes to be represented. But presenting maps and colours in printed media is not just a simple matter of applying any colour. Colors need to be easily interpreted, aesthetic, meaningful and reproducible. I used the tool ColorBrewer (Brewer, 2017), to produce map and graphic palettes, which should be colour-blind safe, and friendly for print, screen and photocopy. Of course, it is not always possible to satisfy all the criteria, and where colour was difficult to use I also used different symbolisations in combination with colours. For the *Coffee Atlas of Ethiopia* (paper IV[a]), this was not an easy task as we had to represent eight coffee classes, as well as much contextual information to help the reader navigate within the maps and pages. We tested the colour schemes many times with users and readers, and then incorporated this feedback into the final versions. For forest classes, I used shades of green (to represent the greenness of vegetation); for the non-forest they are in the same tonal shade, but in blues to purples. For non-coffee forests, I use a light grey (as they are not as important as the coffee areas). I symbolised the very sparse coffee gardens with a coffee bean symbol, the coffee growing area and towns with *jabenas* (Ethiopian coffee pots). To give the reader context and navigational pointers we added locality names, transport layers (roads, trainlines, etc.) and protected areas. Finally, we added to the background elevation and hill shade to give an indication of the terrain (Figure 13).

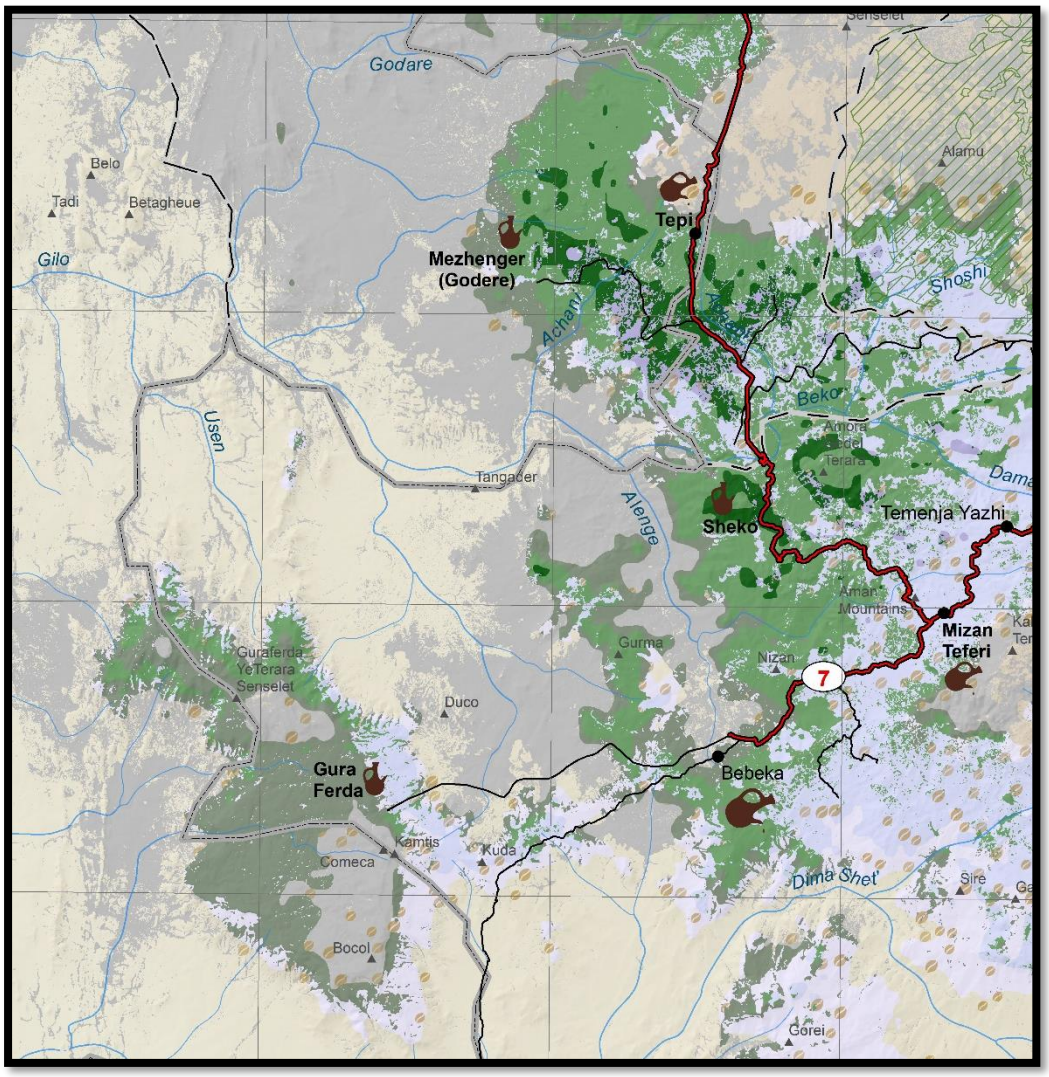


Figure 13. Detail from the Coffee Atlas of Ethiopia *(Paper IV[a]), illustrating colours and symbolisation used.*

Other media

Whilst producing all our outputs, paper and visuals we also worked closely with various journalists and the BBC to produce videos and interactive maps and visuals, to bring the findings to life and to gain a wider audience, and this is reviewed in Appendix VII.



Figure 14 A 1950s Gaggia Expresso machine (still in use in Eritrea). Image: Lucia Tarantola, Wikimedia

In the 1950s the coffee drinking sector was revived with the use of the newly invented and carefully marketed espresso machine

10. The manuscripts

Overview

The manuscripts present the major outputs from this thesis. As already highlighted, the pressures on the planet, including climate change, are ever present, as is the need to understand the likely influence on the planet's living biota. In August 2017 it was highlighted that it is 'infeasible' to limit global warming to 1.5 ^{o}C (Marcucci, Kypreos and Panos, 2017), without geoengineering. *Coffea arabica* is a globally important species, being a major traded commodity, a livelihood provider for many millions of small-holder farmers, and is known and loved by the greater majority of the planet's population. The maturation of SDM modelling techniques, conservation algorithms and the availability of high-resolution climate data and projections, allows us to understand the likely influence of climate change on Arabica coffee. Combining all this with the many output types allows us to model and communicate the different outcomes for *C. arabica* in the form of a formal (IUCN) extinction risk assessment under a changing climate, to a wide audience with multiple motivations.

In these manuscripts (and within the discussion) I tackle these questions, with answers (and the uncertainty), and show the results for a diverse audience.

Paper II. Resilience potential of the Ethiopian coffee sector under climate change.

Published: Nature Plants.

Moat, J., Williams, J., Baena, S., Wilkinson, T., Gole, T.W., Challa, Z.K., Demissew, S & Davis, A.P. (2017). Resilience potential of the Ethiopian coffee sector under climate change. *Nature Plants 3*(7): 17081. https://doi.org/10.1038/nplants.2017.81

Status:

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Authors contributions:

J.M. and A.P.D. conceived and led the study; A.P.D. and J.M. led the project; all authors collected data; J.M., A.P.D., J.W., S.B. and T.W. analysed and processed the data. J.M. and A.P.D. wrote the paper with contributions from all authors.

Pages: 14 + 20 (supplementary material)

nature plants

ARTICLES

PUBLISHED: 19 JUNE 2017 | VOLUME: 3 | ARTICLE NUMBER: 17081

Resilience potential of the Ethiopian coffee sector under climate change

Justin Moat[1,2]*, Jenny Williams[1], Susana Baena[1,2], Timothy Wilkinson[1], Tadesse W. Gole[3], Zeleke K. Challa[3], Sebsebe Demissew[1,4] and Aaron P. Davis[1]*

Coffee farming provides livelihoods for around 15 million farmers in Ethiopia and generates a quarter of the country's export earnings. Against a backdrop of rapidly increasing temperatures and decreasing rainfall, there is an urgent need to understand the influence of climate change on coffee production. Using a modelling approach in combination with remote sensing, supported by rigorous ground-truthing, we project changes in suitability for coffee farming under various climate change scenarios, specifically by assessing the exposure of coffee farming to future climatic shifts. We show that 39–59% of the current growing area could experience climatic changes that are large enough to render them unsuitable for coffee farming, in the absence of significant interventions or major influencing factors. Conversely, relocation of coffee areas, in combination with forest conservation or re-establishment, could see at least a fourfold (>400%) increase in suitable coffee farming area. We identify key coffee-growing areas that are susceptible to climate change, as well as those that are climatically resilient.

Arabica coffee (*Coffea arabica*) provides Ethiopia with its most important agricultural commodity, contributing around one quarter of its total export earnings[1]. In 2015/16, Ethiopia exported around 180,000 metric tonnes of coffee[2] at a value in excess of 800 million USD, making it Africa's largest coffee producer and the world's fifth largest coffee exporter[2], despite the fact that around half of the coffee produced each year is consumed in-country[3]. Coffee farming provides a livelihood income for around 15 million Ethiopians (16% of the population), based on four million small-holder farms[2,4].

In Ethiopia, coffee is produced within specific agro-ecological zones, over numerous geographical and political boundaries. At least 80% of Ethiopia's coffee comes from forests, forest-like habitats, or farms with shade (canopy) cover, representing land coverage of around 19,000 km^2 (Fig. 1) with around another 4,000 km^2 (c. 20%) grown in small plots in partial shade or full sun. Most of the coffee is grown in areas that are covered, or were previously covered[5], with humid evergreen forest: Moist Afromontane Forest (MAF) and Transitional Rain Forest (TRF)[6]. MAF and TRF are found at 650–2,600 m (450–3,000 m including extremes), although coffee is mostly confined to 1,200–2,200 m. Coffee farming is also undertaken in association with a drier type of vegetation, classified as Dry Afromontane Forest[6], such as that found in the Harar Zone (Fig. 1). The main coffee-growing areas of Ethiopia are found within the south-west and south-east (Oromia Region and Southern Nations, Nationalities and Peoples' Region), with modest and minor production in the north (Amhara Region and Benishangul–Gumuz Region, respectively) (Fig. 1).

Coffee farmers and other coffee sector stakeholders in Ethiopia and East Africa report that coffee production has been negatively influenced by changes in climate. These changes include: an increase in the uncertainty of yearly weather patterns, particularly in precipitation variability and timing of the wet season; an extension of the dry season (shortening of the wet season); a more extreme (drier and hotter) end to the main dry season; more intense (extreme) weather (heavier rain, hotter days); and warmer nights[7,8].

Historical climate data shows that the mean annual temperature of Ethiopia has increased by 1.3 °C between 1960 and 2006, at an average rate of 0.28 °C per decade[9] and by 0.3 °C per decade in the south-west[10] and Amhara in the north[11]. These temperature increases have been most rapid in the main wet season (July to September) at a rate of 0.32 °C per decade[9]. Analyses of extreme temperature changes in various coffee-growing areas indicate positive trends for maximum temperature, warm days, warm nights and warm spell duration; and negative trends for cool days, cool nights, and cold spell duration across different eco/agricultural environments (pastoral, agro-pastoral and highland), although some of the trends are not statistically significant[12]. The strong variability within Ethiopia's annual and decadal rainfall makes it difficult to detect long-term, country-wide trends[13]. Despite these limitations, studies show: that February to May[14] and June to September rains have declined[13,15,16]; a 15–20% reduction in rainfall since the mid-1970s[17] and late 2000s in southern, south-western and south-eastern Ethiopia, particularly in the period of the initial early (February to March) rains in the south-east and east[18,19], with an increase in drought frequency in all parts of Ethiopia during the last 10–15 years[16]; a decrease in June to September precipitation in the Greater Horn of Africa by approximately 1 s.d. during the period 1950–1989, corresponding to decreases of over 30 mm per decade throughout much of the Ethiopian Highlands[20]; and a downward trend in rainfall of 0.4 mm per month per year over the south-western region in the period 1948–2006[10].

The mean annual temperature of Ethiopia is projected to increase by 1.1–3.1 °C by the 2060s, and 1.5–5.1 °C by the 2090s, depending on the emission scenario[9]. Climate model projections under the emission scenarios A2 and B1 show Ethiopia warming in all four seasons across the country[21]. Projections from different General Circulation Models (GCMs) are broadly consistent in

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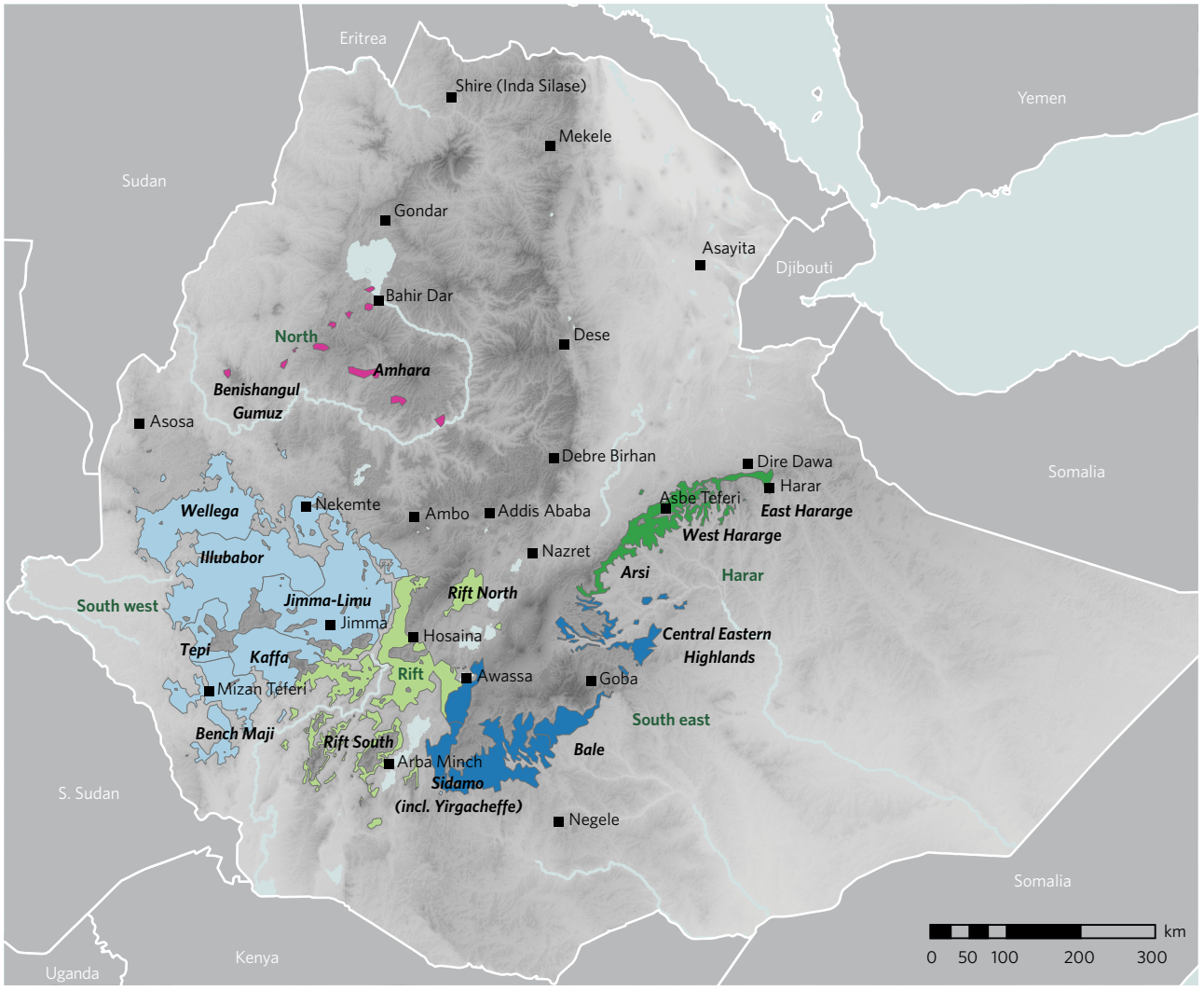


Figure 1 | The main coffee growing zones and areas of Ethiopia. The coffee zones represented by coloured polygons: red/pink, North Zone (coffee areas: Amhara and Benishangul Gumuz); light blue, South West Zone (coffee areas: Wellega, Illubabor, Jimma-Limu, Kaffa, Tepi and Bench Maji); light green, Rift Zone (coffee areas: Rift North and Rift South); dark blue, South East Zone (coffee areas: Sidamo, Yirgacheffe, Bale and Central Eastern Highlands); dark green, Harar Zone (coffee areas: Arsi, West Hararge and East Hararge).

indicating slight increases in annual rainfall in Ethiopia[22,23]. However, it should be made very clear that precipitation projections vary considerably in their agreement; some increases are negligible; the variability for GCM change is extremely high[24]; and for some regions of Ethiopia GCMs do not agree on the direction of change[21].

It is imperative to better understand the influence of climate change on coffee farming in Ethiopia, given the importance of coffee production and consumption for this country. The impacts of observed and projected changes in climate on coffee farming in Ethiopia are largely unknown. The only available climate change study for Ethiopian coffee is for native populations of Arabica coffee, using a single species distribution model (SDM), forest-only data and one GCM[25].

In order to quantify the influence of climate change on coffee farming in Ethiopia, we collated and collected high-quality ground-point data, from across the Ethiopian coffee landscape and beyond, then modelled using an ensemble SDM approach, which was overlaid with Landsat 8 satellite imagery[26] to accurately delimit the main coffee production areas (humid forest). This approach, in conjunction with the use of multiple migration scenarios, fine-level suitability thresholding, multiple GCM appraisal and rigorous ground-truthing (of models and remote sensing outputs), constitutes a significant advancement over previous coffee climate change analyses generally[25,27–33]. Nine environmental variables (from BIOCLIM[34]) were used to understand the current climate conditions for coffee farming, and to project suitable growing areas for the future. Using these data and methods we quantify the potential outcomes of climate change on coffee production across the coffee landscape of Ethiopia until 2099. Our analyses are primarily focused on exposure (based on climate scenario projections from GCMs). The two other aspects of climate change vulnerability, sensitivity and adaptive capacity[35,36], have not been directly addressed, although it should be noted that Arabica coffee is identified as a climate-sensitive species with a low adaptive capacity[25]. The potentially beneficial influence of elevated CO_2, and compounding negative influences (for example, pests, diseases and deforestation) were not included in our analyses, but are discussed.

Results

Model projections overview. We modelled Arabica coffee suitability for Ethiopia using the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3)[37], across four time intervals (1960–1990, 2010–2039, 2040–2069 and 2070–2099; Supplementary Fig. 1), using

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Box 1 | Migration scenarios.

Six migration scenarios used in the modelling (see Supplementary Fig. 5 for further details, and Methods for processing details).

(A) Full Migration. Plants can grow in any suitable niche (can move anywhere).
(B) Plants can only grow within known niche (can only move within presently predicted niche).
(C) Plants can only grow within suitable forest cover, within any suitable niche (can move within suitable forest).
(D) No Migration. Plants can only grow within suitable forest cover and only in suitable known niche (restricted to present-day forest cover and suitable niches).
(E) Plants can only grow within suitable niche but only if niche does not drop outside of suitability during any 30-year time period.
(F) Plants can only grow within suitable forest cover and suitable niche, but only if niche does not drop outside of suitability during any 30-year time period.

Box 2 | Niche classifications.

Environmental niche (coffee suitability) categories (see Supplementary Fig. 2, Methods and Supplementary Information for category threshold visualization and statistics).

(1) Unsuitable. Coffee farming is barely possible to impossible.
(2) Marginal. Coffee farming is possible but often problematic, with poor and very inconsistent yields.
(3) Fair. Coffee farming possible and sometimes good but may require additional inputs (for example, irrigation, good shade and pruning). Yields poor in years with low rainfall.
(4) Good. Coffee farming good, with the potential for consistent, high-quality yields. Yield and quality may be negatively affected in some years (during adverse weather conditions, especially low rainfall and high temperatures).
(5) Excellent. Coffee farming good to excellent, with the potential for consistent, high-quality yields. Yields and quality can be negatively affected by adverse weather conditions, but less likely.

Table 1 | Total suitable niche area change for three selected GCMs.

Scenario (migration – emission)	Area change for low: middle: high outcomes (km^2 with percentage area remaining in parentheses)			
	1960–1990	2010–2039	2040–2069	2070–2099
A – A1B	44,820: 44,820: 44,820 (100: 100: 100)	60,996: 66,158: 74,873 (136: 148: 167)	50,387: 58,036: 72,033 (112: 129: 161)	42,247: 51,280: 61,230 (94: 114: 137)
B – A1B	44,820: 44,820: 44,820 (100: 100: 100)	29,192: 35,270: 41,195 (65: 79: 92)	27,110: 29,838: 35,597 (60: 67: 79)	19,553: 24,379: 26,809 (44: 54: 60)
E – A1B	44,820: 44,820: 44,820 (100: 100: 100)	29,192: 35,270: 41,195 (65: 79: 92)	26,287: 29,079: 34,923 (59: 65: 78)	18,427: 23,389: 26,110 (41: 52: 58)
A – A2	44,820: 44,820: 44,820 (100: 100: 100)	62,774: 74,272: 90,527 (140: 166: 202)	54,722: 57,118: 68,728 (122: 127: 153)	42,004: 50,498: 56,371 (94: 113: 126)
B – A2	44,820: 44,820: 44,820 (100: 100: 100)	31,245: 34,904: 42,046 (70: 78: 94)	28,054: 32,138: 33,438 (63: 72: 75)	19,101: 22,468: 27,647 (43: 50: 62)
E – A2	44,820: 44,820: 44,820 (100: 100: 100)	31,245: 34,904: 42,046 (70: 78: 94)	27,617: 31,717: 33,091 (62: 71: 74)	17,648: 21,415: 26,577 (39: 48: 59)
C – A1B	19,142: 19,142: 19,142 (100: 100: 100)	17,451: 20,575: 23,855 (91: 107: 125)	17,330: 19,588: 22,082 (91: 102: 115)	14,479: 17,139: 20,378 (76: 90: 106)
D – A1B	19,142: 19,142: 19,142 (100: 100: 100)	11,370: 14,319: 17,130 (59: 75: 89)	12,131: 12,897: 14,335 (63: 67: 75)	8,604: 11,256: 12,311 (45: 59: 64)
F – A1B	19,142: 19,142: 19,142 (100: 100: 100)	11,370: 14,319: 17,130 (59: 75: 89)	11,817: 12,556: 14,100 (62: 66: 74)	8,377: 10,464: 12,058 (44: 55: 63)
C – A2	19,142: 19,142: 19,142 (100: 100: 100)	19,111: 21,072: 25,040 (100: 110: 131)	18,092: 20,264: 20,742 (95: 106: 108)	14,189: 17,781: 19,225 (74: 93: 100)
D – A2	19,142: 19,142: 19,142 (100: 100: 100)	13,257: 14,177: 16,319 (69: 74: 85)	11,295: 12,983: 14,964 (59: 68: 78)	8,584: 9,933: 13,013 (45: 52: 68)
F – A2	19,142: 19,142: 19,142 (100: 100: 100)	13,257: 14,177: 16,319 (69: 74: 85)	11,105: 12,789: 14,858 (58: 67: 78)	7,910: 9,502: 12,622 (41: 50: 66)

Percentage and km^2 change (that remaining) in surface area for coffee niche suitability, against 1960–1990, for low, middle and high outcomes (see Methods for explanation) for migration scenarios (A–F) and emission scenarios A1B and A2. GCMs: GFDL-CM2.1, CSIRO-MK3.5 and BCCR-BCM2.0. The table is split: the top section contains niche-only scenarios (A, B, E), while the bottom section consists of forest and niche scenarios (C, D, F).

two emission scenarios (A1B and A2), six migration (coffee area movement) scenarios (Box 1; Supplementary Fig. 5), two biological/climatic coffee groups/areas and 23 GCMs, selecting three GCMs for our final analysis (see Methods). Coffee growing suitability was divided into five categories, based on statistical thresholding: Unsuitable, Marginal, Fair, Good and Excellent (see Methods; Box 2; Supplementary Fig. 2). We restrict our narrative here to two migration scenarios: A and D (Box 1), which we refer to as 'Full Migration (A)' and 'No Migration (D)'. The Full Migration (A) scenario represents the (maximum) potential niche (suitability) for coffee in Ethiopia, invoking an assisted migration scenario, where coffee areas can move to newly available niches, regardless of whether there is forest or not (Fig. 2). This scenario would require considerable intervention, including the provision of canopy cover (tree planting) in many places. The No Migration (D) scenario represents the actual (near-minimum; where scenario F is the minimum) coffee-growing surface area, based on the recent past (1960–1990) (Fig. 3). It assumes non-migration of coffee areas, either natural[25] or assisted (by planting coffee and shade cover) and also that there is zero forest loss or gain, but allows for climate change within the niche. Summary data for other migration scenarios are supplied in Table 1 and

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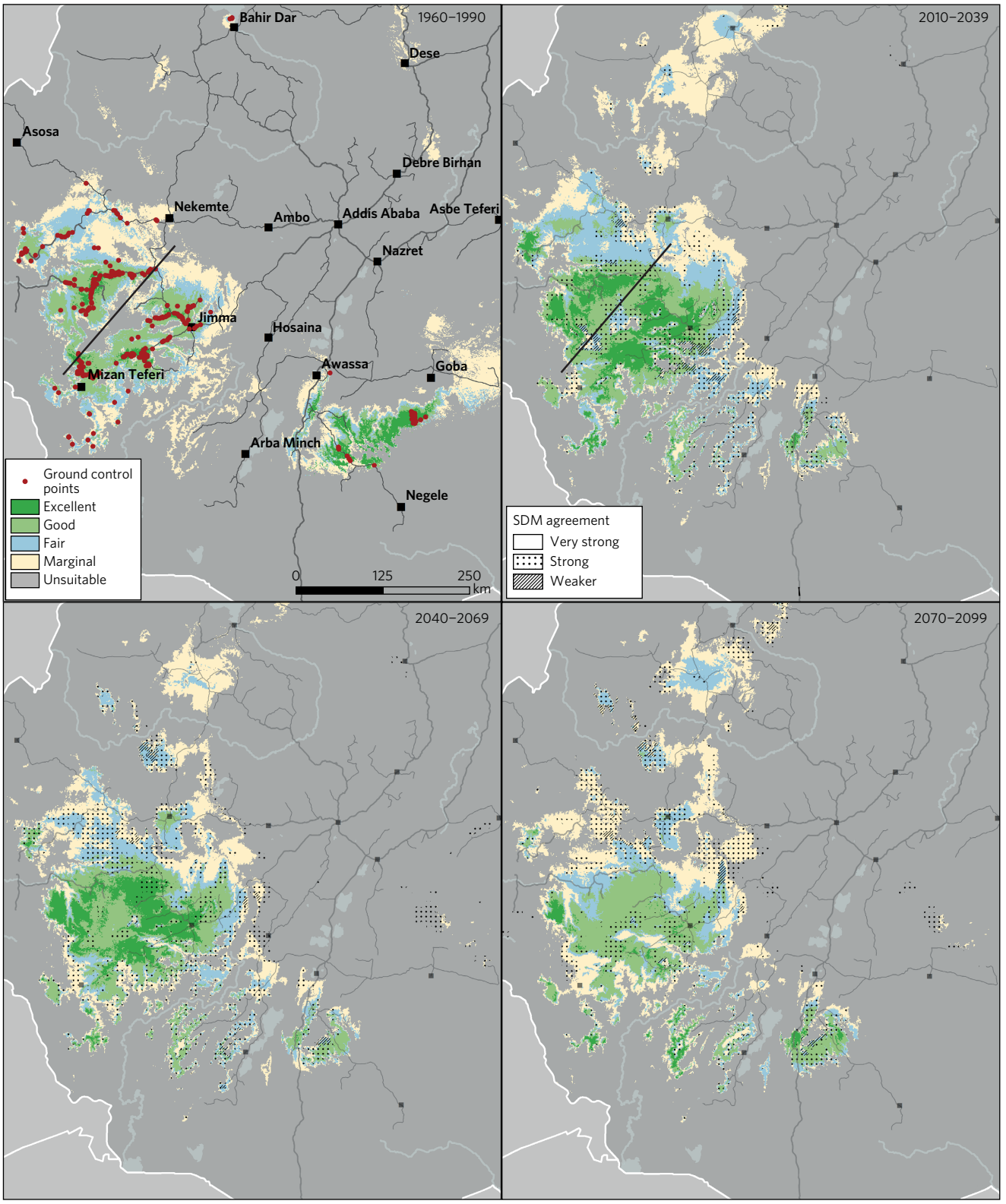


Figure 2 | Future projections for coffee suitability under Full Migration (A) and emission scenario A1B. Median of the three GCMs was used to colour niche suitability. SDM modelling agreement: very strong (average of 86% across study area, for all time periods), solid colour with no overlay; strong (13%), dots overlaid; weaker (1%), diagonal hatching overlaid. The 1960–1990 map shows the ground control data points used in this study and major place names (removed for clarity in subsequent maps). All maps show major roads (as dark lines) for navigation. Diagonal lines on 1960–1990 and 2010–2039 maps show the location of the elevation profile given in Fig. 6.

Supplementary Figs 7 and 8. In our modelling, there were no considerable differences between A1B and A2 (CMIP3 (ref. 37)), and so we restrict our main narrative to scenario A1B, which is the lower emission scenario of the two; results from the A2 analysis and migration scenarios B, C, E and F are supplied (Table 1; Supplementary Figs 7 and 8). We also review the more

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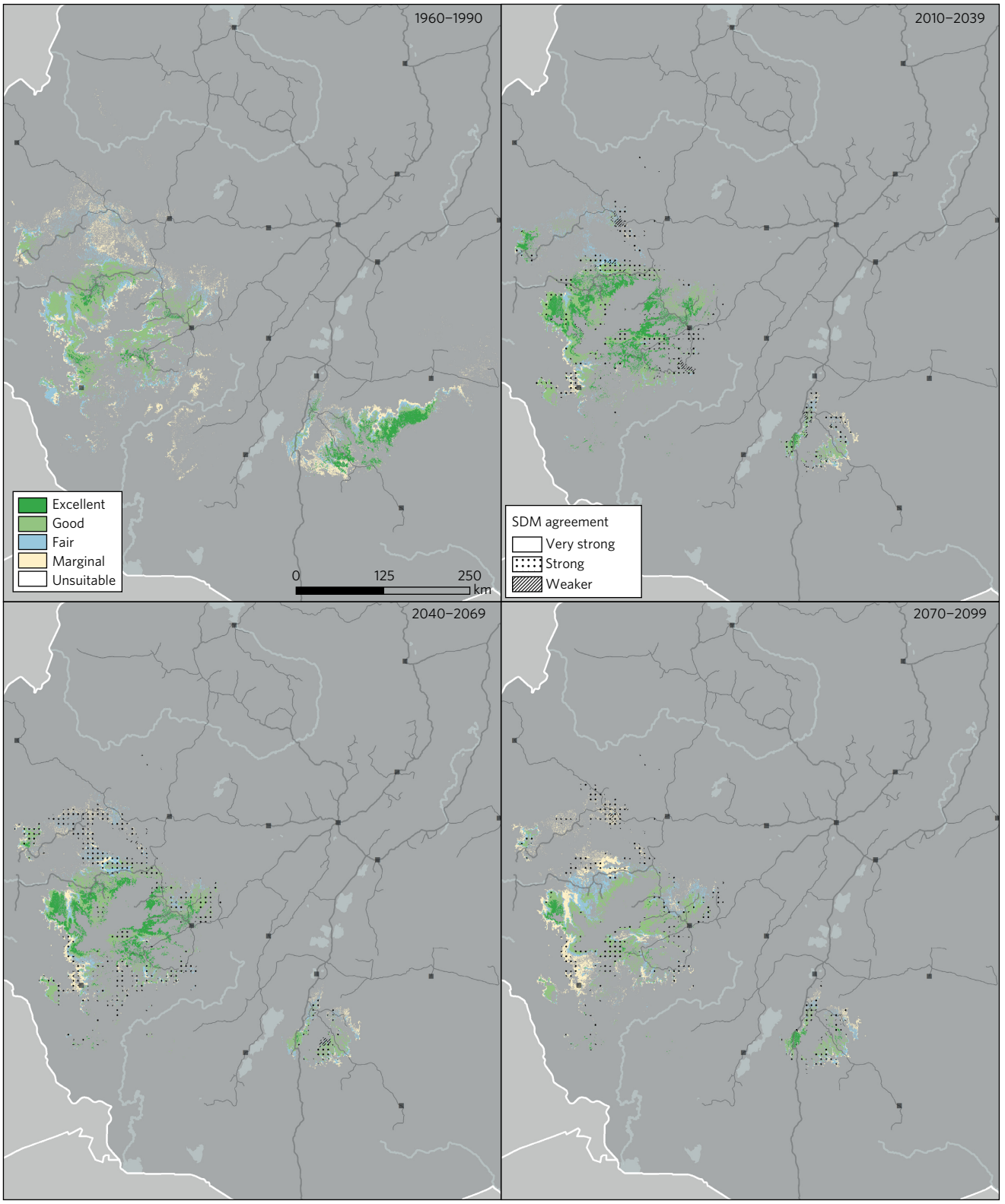


Figure 3 | Future projections for coffee suitability under the No Migration scenario (D) and emission scenario A1B. Median of the three GCMs used. All maps show major roads (as dark lines) for navigation. SDM agreement symbolism as in Fig. 2.

recent Coupled Model Intercomparison Project phase 5 (CMIP5)[38] Representative Concentration Pathway (RCP) Scenario 8.5 (RCP8.5) emission scenarios, following Knutti & Sedláček[39] (see Methods and Discussion). In the following two sections, we provide percentages for the middle range projections and their area (coffee niche suitability in km^2), based on the three selected GCMs (Bjerknes Centre for Climate Research, Bergen Climate Model, Version 2 (BCCR-BCM2.0); Centre for Australian Weather and Climate Research Mark, 3.5 (CSIRO-MK3.5); and Geophysical Fluid Dynamics Laboratory, USA, Coupled Climate Model 2.1 (GFDL-CM2.1)). The range of values for low and high range outcomes, which are also based on the above three GCMs, are given in Table 1.

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Figure 4 | Future projections for coffee suitability under the scenarios of Full Migration (A) and No Migration (D) across emission scenarios A1B and A2. Error bars represent the SDM area (km^2) model variability (low and high model outcome) within the three GCMs (GFDL-CM2.1, CSIRO-MK3.5 and BCCR-BCM2.0). See Methods (section 'Selection of GCMs') and Table 1 for further details. A1B-A is the scenario used in the Results and Discussion.

Projections 1960–1990 to 2010–2039. We see a large increase (Figs 2, 4 and 5) in coffee area suitability under the Full Migration (A) scenario within the present/near future (2010–2039), compared to the recent past (1960–1990). This is due to a dramatic increase in the area available (and suitable) for coffee at higher elevation, as temperatures increase, particularly in the South West Zone and to a lesser extent the North Zone (see Fig. 1 for zone localities). The overall shift for each time period is shown in Fig. 6. If we look at the south-western plateau (South West Zone) there is a vast area (in excess of 15,000 km^2) that comes into suitability in 2010–2039,

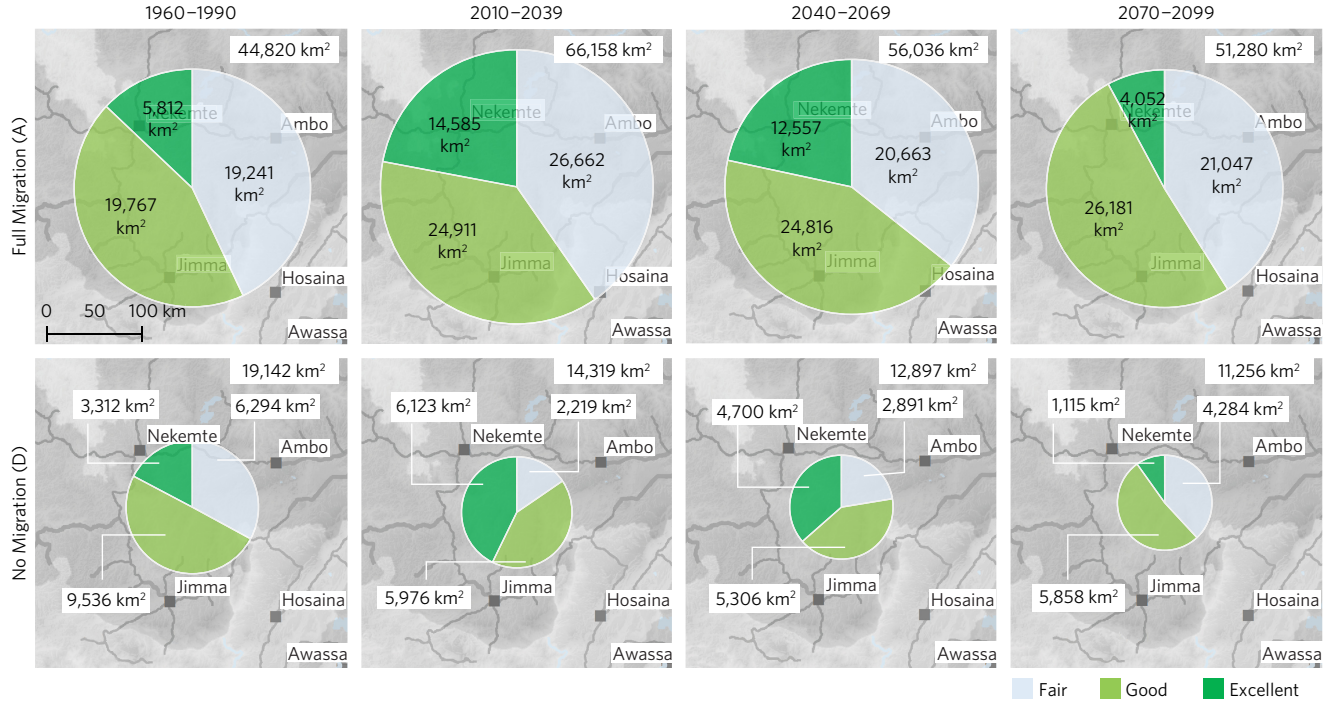


Figure 5 | Availability of suitable coffee niche in km^2 for migration scenarios of Full Migration (A) and No Migration (D). Total suitable area is given in the top right of each pie chart box. See Table 1 and Supplementary Table 1 for all metrics. Scenario A: coffee plants can grow in any suitable niche (can be moved anywhere); scenario D: coffee plants can grow only within suitable forest cover and only in a suitable known niche (restricted to movement within present-day forest cover and suitable niches). See Supplementary Fig. 5 for further details. The background is part of south-eastern Ethiopia, and is given to provide a scale for the ground area.

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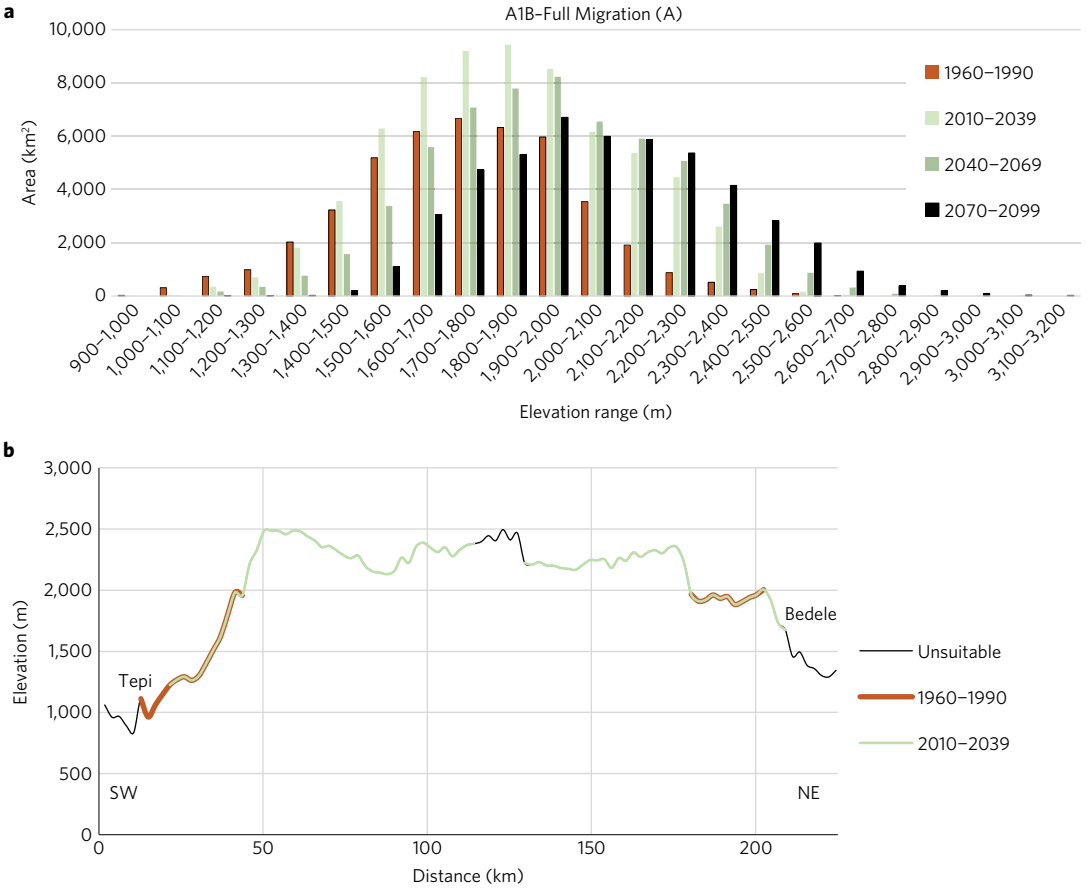


Figure 6 | Histogram and profile for elevation shifts. a, Histogram of elevation range for Full Migration (A) scenario, under emission scenario A1B. The change in ranges shows a potential shift of 32 m in elevation per decade (see Methods). **b**, Elevation profile of the South West Zone with coffee suitability for 1960–1990 and 2010–2039. Location of profile across the south-western plateau, running from south-west corner (SW) to north-east corner (NE), as shown in Fig. 2.

but which declines as the century progresses (Fig. 6). We originally considered the possibility that this expansion in suitability might be due to the 'East African Climate Paradox'[14], where forecasts (from GCMs) show an increase in rainfall for East Africa compared to actual declines in rainfall (from the 1980s to present day)[14,40]. We do not see this in our data or analyses; the increase in suitable area for 2010–2039 is as a result of the interaction between climate change and the topology of Ethiopia (see Discussion).

Under the No Migration (D) scenario (Figs 3–5) and the middle range projection, from 1960–1990 to 2010–2039 there is a decrease of 25% (19,142 km^2 to 14,319 km^2) across the Fair to Excellent coffee suitability niche categories. Over the same period there is an increase of 85% (from 3,312 km^2 to 6,123 km^2) in the Excellent category, which accounts for the corresponding decreases in the Fair and Good categories (Figs 4 and 5; Supplementary Figs 7 and 8). Under Full Migration (A) there is a 48% increase (44,820 km^2 to 66,158 km^2) in the Fair to Excellent categories over this period (Box 2; Table 1; Figs 4 and 5). A projection with profound implications is the early loss (2010–2039) of almost the entire Bale coffee area and eastern parts of the Sidamo coffee area (Figs 2 and 3). This outcome is consistent across all three GCMs, and all migration and emission scenarios (Figs 2 and 3). This result appears dramatic given that much of this area currently falls within the Excellent coffee niche suitability category. In the Discussion, we offer a possible explanation for this critical finding.

Projections 2010–2039 to 2070–2099. Over the rest of this century (until 2099), the models forecast a general reduction (km^2) in coffee niche suitability, but the degree of reduction is highly dependent on the migration scenario (Box 1; Table 1; Figs 4 and 5; Supplementary Figs 5, 7 and 8). Under the No Migration (D) scenario and the middle range projection (Fig. 5) there is a 21% decrease (from 14,319 km^2 to 11,259 km^2) in the suitable coffee niche, from 2010–2039 to 2070–2099. We also see a similar reduction under the Full Migration (A) scenario, where there is a 22% decrease (from 66,158 km^2 to 51,280 km^2) over the same period (Fig. 5). For both No Migration (D) and Full Migration (A), the most obvious difference is the substantial decrease in the Excellent category: 82% (from 6,123 km^2 to 1,115 km^2) for No Migration (D), and 72% (from 14,585 km^2 to 4,052 km^2) for Full Migration (A) (Table 1; Figs 4 and 5), from 2010–2039 to 2070–2099. During 2040–2069, coffee suitability holds quite well, due to niche potential at higher elevations (as the higher ground provides suitability for coffee), for Full Migration (A) and No Migration (D) and most of the other migration scenarios (Figs 2–5). Most of the increases and stabilities in suitability are distributed in the main South West Zone (Figs 1–3 and 6). The Arsi, East Hararge and West Hararge coffee areas (Harar Zone) do not show any niche suitability, for any of the modelling, for any future time period, and this result receives strong model agreement. Environmentally, they are ill suited to coffee growing now and do not improve in the future (Figs 1–3 and 6). Under the Full Migration (A) scenario, new areas of suitability develop, especially in the Amhara, Benishangul–Gumuz and Rift South coffee areas (Figs 1–3), mostly in the Fair and Good categories, but with lower model agreement (Figs 2 and 3).

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Full Migration versus No Migration. Comparing Full Migration (A) to No Migration (D) over the three future time periods, the percentage differences in the potential coffee niche area are substantial: 2010–2039, 462% (44,820 km^2 to 14,319 km^2); 2040–2069, 450% (58,036 km^2 to 12,897 km^2); and 2070–2099, 455% (51,280 km^2 to 11,256 km^2) (Table 1; Figs 2–6; Supplementary Table 1). This also demonstrates that, in Ethiopia, considerably more land could be used to grow coffee than is currently the case.

Discussion

Modelling considerations. The outcomes of our projections should take into account the assumptions and uncertainties associated with SDMs generally[41], within the regional context[25], and the projection of SDMs with climate change[41]. We have done our utmost to represent assumptions and uncertainties. Predicting future climate with any great certainty is not possible, but by using multiple climate models it is possible to make future projections assuming certain pathways of greenhouse gas emission. These are highly uncertain and cannot be validated, since we have no analogue for future climate. However, climate model projections provide useful estimates of potential future conditions[41], which we can use to explore the sensitivity of coffee production. By comparing different climate models and exploring reasons for the projected change in the coffee farming suitability niche, we can start to understand the vulnerabilities of coffee growing, at least in terms of exposure[35,36], and the level of confidence in the projected change of the niche.

Projections 1960–1990 to 2010–2039. Projections from the recent past (1960–1990) to present/near future (2010–2039) under the No Migration (D) scenario (Fig. 3) agree with our on-the-ground observations for climatic coffee farming suitability, the overall productivity of specific areas[42] and climate station data. Specifically, areas categorized by us as Unsuitable or Marginal generally have poor and inconsistent harvests, produce lower quality coffee and in extreme circumstances (for example, drought episodes) coffee trees experience severe stress or death. We present three examples to illustrate this. (1) In the Zege Peninsula, near Bahir Dar (on the shores of Lake Tana), coffee farming is problematic, with good harvests only every five years. The farmers report (personal communication) that there has been a long-term decline in productivity, from good harvests every year or two in the 1930s, to good harvests every five years (since the late 1990s). We assess the suitability of the Zege coffee locality as Marginal (1960–1990) to Fair (2010–2039), and then Unsuitable (2040–2099), with very strong SDM model agreement (Figs 2 and 3). The main climate constraint for Zege is not the amount of total annual rain, but rather the long dry season (Supplementary Fig. 4). (2) In the central and eastern parts of Wellega coffee area, where the SDM (1960–1990) categorizes suitability as Marginal, farmers and intervention workers report (personal communication) increasingly inconsistent harvests (a good harvest every three years or so), which they attribute to a shift in less rain from the late 1970s and mid-1980s. (3) For the Harar Zone, the niche is categorized as Unsuitable (Figs 1–3), which is a fair representation of conditions there at the present time: coffee farming is mostly suboptimal unless improved agronomy is practised (for example, irrigation, terracing), where the local or micro-climate is more suitable, or where the water table brings sufficient moisture to the soil. During the course of our field survey work we received numerous anecdotal reports (from farmers and coffee sector representatives) of a long-term decrease in rainfall over the Harar Zone and a steady, long-term decline in coffee farming. It seems clear, however, that the conversion to the narcotic khat (*Catha edulis*) has also had a considerable influence on declining coffee production in the Harar Zone. Since at least the 1960s, farmers have moved to growing this more lucrative crop at the expense of coffee farming and best-practice coffee agronomy. Given that there are also no gains in niche suitability in the Harar Zone across any of the modelling to 2099 (Figs 1–3 and 6) and that the modelling is in strong agreement (Figs 2 and 3), it seems that Harar coffee production will continue to decline unless considerable interventions are made. Overall, our modelling projects low-value categorizations (Unsuitable, Marginal, Fair) for the 1960–1990 to 2010–2039 time periods, for areas that are currently suboptimal for coffee farming. One unexpected exception is the Bale coffee area and the eastern part of the Sidamo coffee area (Figs 1–3 and 6), which is projected to be no longer suitable for coffee by 2039. Most of these two areas currently fall within the Excellent niche category. This result has strong to very strong model agreement (Figs 2 and 3). Our explanation for the loss of the Bale area and the climate mechanisms behind declines and increases in coffee suitability are discussed below.

Projections 2010–2039 to 2070–2099. As the century progresses (2010–2039 to 2040–2069 to 2070–2099) the projected outcomes are profound, depending on the migration scenario (Fig. 5). By the end of this century the current coffee-growing niche of Ethiopia could decrease by 39–59% (of the original area; 41–61% suitable area remaining), under our most restrictive migration and emission scenarios (the low-range (area in km^2) outcome, under migration scenario E and emission scenario A2) if no interventions are made (Table 1). The scenario of No Migration (D) (A1B = 45–64% remaining) most closely resembles a 'do nothing' scenario, although forest and tree canopy cover would have to remain stable (no deforestation or afforestation). At the other extreme, under the Full Migration (A) scenario (emission scenario A1B), there would be substantial gains with the potential for a more than fourfold increase in coffee farming area compared to the No Migration (D) scenario.

The main reason for the substantial increase in the area for coffee suitability in 2010–2039, under the Full Migration (A) scenario, is due to higher elevation areas coming into suitability. This is seen predominantly in the South West Zone (Fig. 1), where a huge area (in excess of 15,000 km^2) within the south-western highlands comes into suitability in 2010–2039. After 2010–2039, an elevation ceiling (literally) is reached, resulting in a decline from there onwards. There are of course interactions with rainfall (adding more nuanced changes), but the dominant climatic factor for the expansion is temperature, which is manifest as an upward elevational shift. An elevation profile across the South West Zone (Fig. 6b) illustrates this topographical expansion.

Particularly vulnerable coffee areas over these two time periods, under any migration scenario, include large parts of Wellega, the northern part of Illubabor and Bench-Maji (Figs 1–3 and 6), with variable but mostly strong SDM model agreement for these projections (Figs 2 and 3). All of the five circumscribed coffee zones (Fig. 1) could be negatively influenced to some extent (Figs 2 and 3), particularly at lower altitudes (Fig. 6). The main South West Zone has the most inherent resilience, mainly due to the potential for the coffee niche to improve in suitability at higher elevations (Figs 6 and 7). Across Ethiopia, the most climatically suitable part of the overall niche (the Excellent category; Box 2) is projected to drastically decline in the long-term (Figs 2–5).

Identifying the drivers of change. There has been considerable focus on the influence of increasing temperatures and supra-optimal temperatures on coffee production[8,43]. It is clear from our study, however, that rainfall is also a major contributing factor; as well as this, field observations, climate station data and our weather station recordings show that temperatures rarely reach the extreme limits for Arabica coffee[43] in Ethiopia. Analysis of the BIOCLIM[34] layers reveals that a combination of rainfall, temperature seasonality

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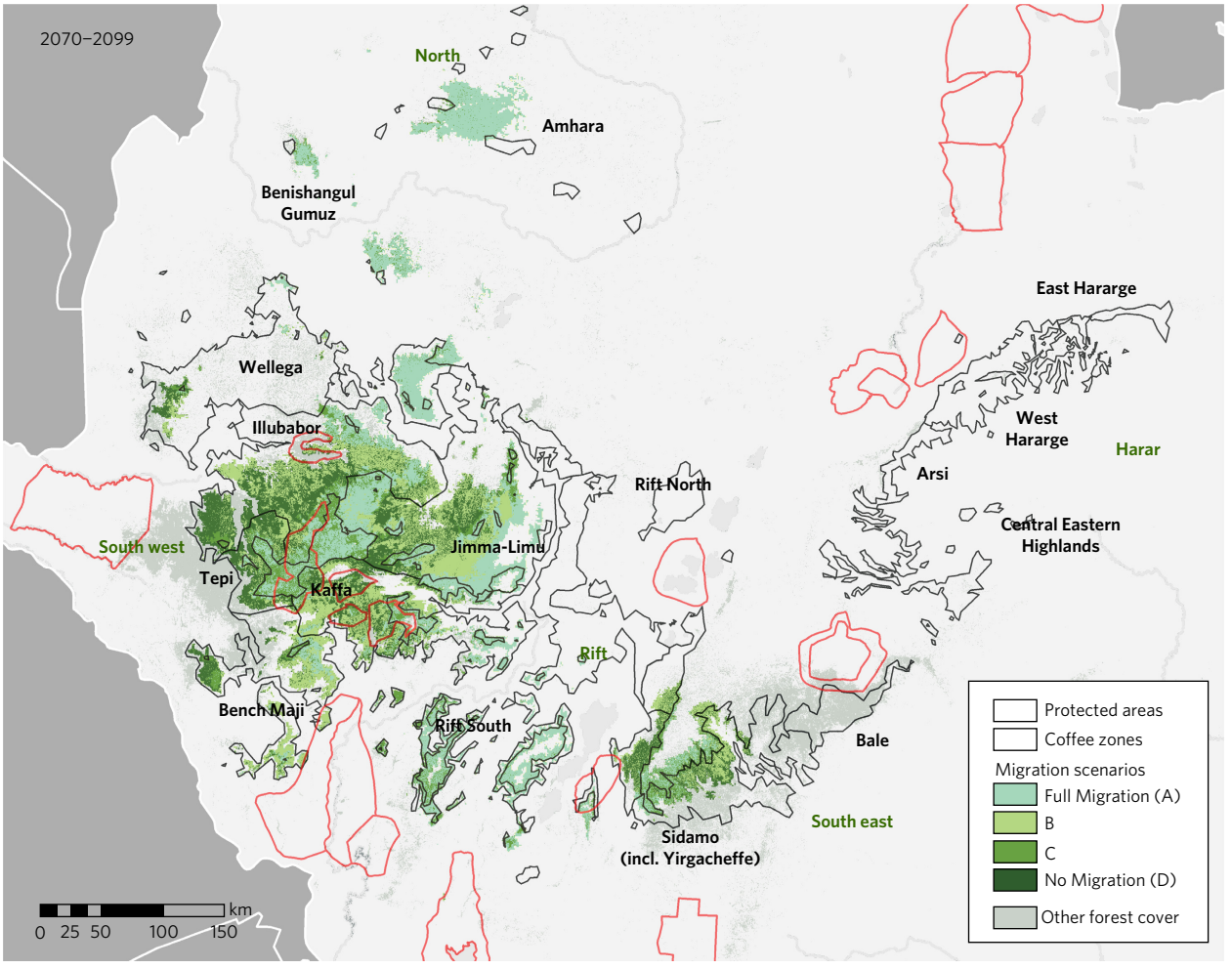


Figure 7 | Projections for coffee suitability 2070–2099 (emission scenario A1B) for scenarios Full Migration (A) and No Migration (D), with main coffee areas (black lines; see Fig. 1) and protected area boundaries[53] (red lines). Migration scenario A (Full Migration (A); green-blue) represents new coffee suitability niche for 2070–2099. Migration scenario B (light green) represents 1960–1990 niches that persist into 2070–2099. Migration scenario C (mid-green) represents new coffee suitability niche for 2070–2099 (as in migration scenario A), but with present-day forest cover. Migration scenario D (No Migration (D); dark green), 1960–1990 niches that still persist into 2070–2099 (as in migration scenario B), but with present-day forest cover. Grey represents other forest cover (with no end of the century coffee niche predicted). Figure 7 should be reviewed with model variability (Fig. 2.). Note, migration scenarios E and F are not represented on this map as they are too small to be visible at this scale.

and annual temperature (east and west of the Rift Valley; Supplementary Tables 2 and 3) were contributing most to the SDMs. By comparing these bioclimatic variables against each of our GCM projections (for emission scenario A1B), we were able to identify the main drivers in our models for change for each of the major coffee zones (Figs 1–3, for context; Supplementary Figs 9–12 show the trends for each zone). Across the entirety of the coffee landscape, the temperature BIOCLIM (BIO1) shows projected temperature increases of 2.7–3.2 °C (under emission scenario A1B) from 1960–1990 to 2070–99 (Supplementary Fig. 9), which is in good agreement with historical records (1960s onwards) and temperature projections from other sources (see Introduction). Temperature seasonality (BIO4) generally increases (Supplementary Fig. 10). Critically, the rainfall BIOCLIMs (BIO12 and BIO18) show little change across this century (Supplementary Figs 11 and 12). Thus, the total rainfall for each area experienced in the present day is key to understanding future suitability, as any increases and decreases in rainfall are mostly projected to be negligible to slight. Harar does show some decline in rainfall towards the end of the century, but the GCMs are in poor agreement (varying in decline of 250, 100 and 0 mm to the end of the century). Any decreases in rainfall for Harar would compound the already unsuitable coffee niche in this area, particularly if temperature increases continue to track future projections. To summarize, the key influencing factors can be viewed as a relatively simple interaction between rainfall and temperature: coffee areas that start with low rainfall cannot tolerate an increase in temperature, especially as rainfall is not projected to change by any considerable amount; temperatures are projected to increase steadily and substantially. If Ethiopian rainfall declines continue (see Introduction), in contrast to the negligible changes in precipitation observed in our projections (Supplementary Figs 11 and 12), they would further amplify the temperature-driven changes identified here. The Harar Zone and some locations within the South East Zone (the latter includes the coffee areas of Bale and Sidamo) have the lowest total rainfall at the present time (<1,300 mm), giving these areas little potential to deal with any temperature increases. In Harar and the South East zones, air temperatures tend to reach a seasonal maxima between January and May, that is, just before or during the onset of the spring rains (and coffee flowering time). These areas would be particularly sensitive to warming and evapotranspiration increases at the end of the dry season, for example, between November and March. This is consistent with projections indicating that increases in potential evapotranspiration may reduce the effective length of the African growing seasons[44].

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The Rift and South West zones have greater rainfall (1,320–1,690 mm) and therefore greater scope to tolerate temperature increases. Areas that are presently too cold (the North Zone and parts of the South West Zone, at higher altitudes), but have enough rainfall, will start to come into suitability as temperatures increase.

A better understanding of the critical relationship between low rainfall (and a corresponding soil moisture deficit) and high temperatures is starting to emerge from our in-country observations of plant stress, in conjunction with the use of climate data logging equipment. At the beginning of the year (January to March), we observe low rainfall and steadily increasing temperatures, resulting in low soil moisture levels, which in some cases reach or exceed the permanent wilting point. For example, in the Bench Maji coffee area we recorded severe plant stress in March (2015), after two months' total rainfall of less than 10 mm per month, an average temperature (based on 1 reading per hour) of 24 °C (minimum 16.4 °C; maximum 34.5 °C) and a volumetric soil moisture content of c. 20%, and soil water potential values of −400 kPa to −1000 kPa (both recorded at 40 cm soil depth). Arabica coffee will perform well in areas with higher temperatures than Ethiopia, but only if there is sufficient rainfall, especially if there are few, short or no periods of the year with a soil water deficit, for example as found in Panama and Costa Rica[45,46]. However, it should be clear that none of our projections would lead to a comparable environment for Ethiopia, given that rainfall is not projected to increase by any considerable amount.

CMIP5 versus CMIP3. In their overview of CMIP5, Knutti & Sedláček[39] compare CMIP5 and CMIP3 and state: "The spatial patterns of temperature and precipitation change are also very consistent. Interestingly, the local model spread has not changed much despite substantial model development and a massive increase in computational capacity." Our SDM results show no considerable differences between A2 and A1B, so if we see scenarios that fall within our present A2 and A1B we would expect similar results. Following Knutti & Sedláček[39] and comparing RCP8.5 with A2, we are provided with an indication of likely differences. The only substantial difference seen is an increase in annual mean temperature (BIO1), with an average additional increase of 0.9 °C (Supplementary Fig. 9), and an increase in temperature range between GCMs. We see some difference in rainfall between A2 and RCP8.5, with projections for increased rainfall (North and Harar zones), but with large disagreement between GCMs. These increases are unlikely to be sufficient to compensate or override projected severe temperature increases, although in the North Zone it is possible that some areas could move to higher suitability under this pathway (Supplementary Figs 11–14 and 16–17). The larger increase in temperature observed for RCP8.5 would indicate that both the A2 and A1B scenarios could be more conservative, compared to RCP8.5. It is also possible that the North Zone, which comes in as a new area in our CMIP3 future predictions, could come into better conditions under RCP8.5, but the increase in rainfall is slight and highly variable (Supplementary Figs 11 and 12). It should be reiterated that RCP 8.5 is the most extreme emissions scenario of the new CMIP5 pathways. Reviewing all of the RCPs for CMIP5 (which for the first time includes a low-emission mitigation scenario), these pathways are likely to deliver a broader range of outcomes. Overall, and as demonstrated by Knutti & Sedláček[39], CMIP5 scenarios give higher warming compared to CMIP3. If temperature change trends track according to (CMIP5) RCP8.5, we would see an amplification of the negative changes identified here using CMIP3.

Other influences. Our modelling does not include the potential influence of elevated CO_2 concentrations in the atmosphere, even though it has been shown that this may have a beneficial physiological influence on coffee, due to improved (leaf) water-use efficiency, which may mitigate high temperatures, at least where there is unrestricted water supply and high relative humidity[43]. Free air CO_2 enrichment experiments show that trees are more responsive than herbaceous plants to elevated CO_2[47] and that elevated CO_2 benefits plant species under drought conditions[48,49], although research indicates that the influence of CO_2 enrichment for crop production may be over-emphasized[50]. If projected increases in CO_2 prove to have a substantial role in mitigating the impact of drier, warmer conditions on coffee production, then our projections of climate exposure could be over-estimated. However, in Ethiopia we observe that drought (water stress) is one of the major causes of crop failure for coffee, and severe drought (lethal water stress) the most significant climate-related cause of plant fatality. We argue, therefore, that while there could be benefits from elevated atmospheric CO_2, drought (in its duration, timing and severity) may far outweigh these gains in the longer term. One might also contend that the forest will change as the climate changes, including responses to elevated CO_2. In this study, we review changes in niche and not forest, although our scenario of Full Migration (A) would encompass a broad spectrum of vegetation change (species and forest composition) within the humid forest vegetation class (MAF and TRF[6]). As well as increasing drought stress, high deforestation rates[5] and particularly their influence on local and regional climate are likely to override the benefits of atmospheric CO_2 enrichment for forest performance and survival and the physiological behaviour of Arabica coffee. We also have little knowledge about the potential influences of pests and diseases, although these are likely to have a compounding negative influence under a warming climate[25,51].

Migration scenarios and interventions. Under the Full Migration (A) scenario, there would be substantial potential to increase coffee farming and thus production volumes. As outlined above, comparison between Full Migration (A) and No Migration (D) (no migration, no forest loss) scenarios shows that the potential to increase the coffee growing area, over the three future time periods (2010–2039, 2040–2069 and 2070–2099), is at least fourfold (>400%), although the niche peaks in 2010–2039 (Table 1; Figs 4–7; Supplementary Table 1). Most of this change comes from up-slope migration to higher elevations. Under Full Migration (A) (emission scenario A1B) there would be a projected altitude shift for overall coffee suitability of 32 m per decade, from 1960–1990 to 2070–2099 (Fig. 6), with a considerable change in the extreme upper limits to 2,800–3,300 m (from 2,200–2,600 m). The emergence of coffee suitability areas at higher altitudes (to those existing now) is projected over a large area of the south-western Ethiopia plateau, but also in areas of the North Zone (Amhara and Benishangul–Gumuz coffee areas), Rift Zone (Rift South area) and South East Zone (Sidamo coffee area), although with different levels of model agreement (Figs 2 and 3). For the Full Migration (A) scenario to be realized, significant intervention would be required, including the planting of shade cover or the restoration of humid forest cover for areas with little or no present-day forest cover (Fig. 7). A concerted effort would be needed to identify and establish new coffee areas at higher altitudes, with particular attention placed on competing land-use issues (for example, existing land-use ownership, nature conservation sites), soil and micro-climate suitability and access to roads and other infrastructure. Shifts could also occur without major intervention, as farmers realize the potential for growing coffee in their upland areas. Field observations made by us in 2015 show that locations in the North Zone are already being developed as new coffee areas (in correspondence with our projections; Fig. 2), at altitudes in excess of 2,500 m (not previously seen for coffee

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farming in Ethiopia), indicating that assisted migration is already underway.

Resilience built via the migration of coffee farms could be supplemented with (location- and time-specific) improvements in coffee productivity (kg per hectare; for example, by increasing soil fertility and pruning) and quality (kg per $; for example, better harvesting and post-harvest processing), in order to offset unit area reductions in environmental suitability. In addition, there is scope for investing in locally appropriate, cost effective agronomy adaptations (such as mulching, irrigation, improved shade management and terracing). Irrigation would provide the single most effective adaptation measure, especially where implementation costs are low, for example, the diversion of nearby streams and rivers. Our projections would serve to provide a framework for the likely success, timing, duration and location of interventions.

Wild coffee forests. Ethiopia's wild coffee forests have considerable fundamental value as the main storehouse of *C. arabica* (Arabica coffee) genetic resources[25], with specific benefits for the coffee sector, locally, regionally and globally[52]. Most directly, indigenous Arabica coffee plays a key role in Ethiopian coffee production as an important source of planting material for farms via seed and seedlings. Protection of these resources should thus be seen as a key part of a resilience strategy. Using all migration scenarios (to 2070–2099), but selecting scenario E to represent the most resilient areas (refugia), provides an indication of which protected areas might have value as reserves for coffee genetic resources (Fig. 7). This exercise identifies protected areas in Kaffa (Kaffa Biosphere Reserve) and northern Illubabor (Yayu, a UNESCO registered Coffee Forest Biosphere)[53], although Yayu would have limited long-term potential unless contiguous areas at higher altitudes are included in the delimitation of its core area. Another important consideration is the preservation of specific coffee origins (and their unique flavour profiles), some of which are identified in the modelling as highly susceptible to negative climate change influences, including the coffees of Harar and Bale.

Summing up. Timely, precise, science-based decision making is required now and over the coming decades, to ensure sustainability and resilience for the Ethiopian coffee sector. Our projections show an overall negative influence, due to climate change, across this century for the present coffee growing landscape. Despite this, there is the potential to increase the area where coffee can be grown (by at least fourfold) via relocation and expansion, even if climate change tracks to our projections, although this would have to be done in combination with forest conservation and re-establishment. We also identify key coffee areas that could be climatically resilient, even without major intervention, at least until the end of this century.

Methods

Mapping the extent of humid forest in Ethiopia. A map of humid forest cover (TRF/MAF[6], and comparable agroforestry environments; Supplementary Fig. 6) was produced from Landsat 8 imagery (http://landsat.usgs.gov/landsat8.php)[26], downloaded for December of 2013 to February of 2014 (http://earthexplorer.usgs.gov (38 images covering 24 scenes)). The images were atmospherically corrected using the Fast Line-of-sight Atmospheric Analysis of Hypercubes algorithm (FLAASH) in ENVI 5.1 (ref. 54) to obtain surface reflectance values. To produce a cloud-free composite, the images were processed to identify clouds and cloud shadows using the Fmask 3.2 algorithm[55]. ERDAS Imagine 2013 was used to produce Normalised Difference Vegetation Indexes[56] from the surface reflectance cloudless composites. Finally, we produced a Normalised Difference Vegetation Index composite using two thresholds to identify the humid forest.

A set of 300 training data points were used to identify the most appropriate thresholds and the individual maps were combined in ArcGIS ver. 10.1 (Environmental Systems Research Institute (Esri)). Testing of the final map yielded an accuracy assessment of 97%. The humid forest map was uploaded to Google Earth for review, as well as large-format mobile phones (Samsung Note II, GT-N7100) using Locus Map Pro 3.1, Asamm Software, Praha, for validation during eight fieldwork trips (2014–2016), with an emphasis to identify and remove non-coffee production areas (for example, tea, mango, avocado plantations and commercial forestry).

Point data and ground-truthing. We collected 3070 data points (Supplementary Fig. 3), of which 1624 were coffee presence data points (1446 non-coffee points), comprising 824 historical (1941–2001) and 800 contemporary (2013–2015) points (with coffee production type, forest cover and condition, and global positioning system (GPS) data recorded). To reduce sampling bias and sampling errors, the ground data was filtered: historical data points collected before 2001 (early-generation GPS, herbarium specimens and literature records) with an accuracy lower than 1 km were rejected; multiple points falling within a 1 km^2 grid were reduced to a single point; any points covering locations with significant interventions (all irrigated and high water table areas) were removed. This left 381 points to build the final SDM. Many of the data points appear to lie close to roads, although a considerable amount of data was collected on foot (c. 40%). There were no indications of a road-like bias in our SDMs. In well-sampled studies, sampling along roads should not represent a bias issue[57], especially where roads cut across numerous environmental gradients, as in Ethiopia. Moreover, the niche and landscape were very well sampled (Supplementary Fig. 3). We double-checked to see if our sampling would show any significant sampling bias by comparing histograms of elevation versus percentage sampling. The range of elevations sampled by the 3,070 data points was 426–3,877 m, which is much greater than the range (991–2,263 m) for the 381 points used for the SDMs. Both histograms showed consistent sampling across 250 m elevation bands.

In addition to the 3070 original points, an additional 1028 points for coffee presence and absence were collected after the initial modelling (2015). These points were used to informally validate the modelling and remote sensing, although no mapping or analyses were undertaken with these data. The 800 contemporary data points (2013–2015) and the additional 1028 data points (2015–2016) were collected during ten field missions, covering c. 30,000 km by road and on foot (plots and transects), across almost the entire coffee landscape of Ethiopia. During our fieldwork, we also informally interviewed farmers for perceived changes in coffee farming, on a year-by-year and generation-by-generation basis.

SDM—the niche. There has been much discussion about the actual niche represented by an SDM and particularly the question over realised niche versus fundamental niche. Most SDM studies identify the realised niche[58]; the closer the realised niche gets to the fundamental niche, the better the projections are likely to be. When using bioclimatic variables, the results will tend towards the fundamental niche, especially when extrapolating to new areas (for example, introduced ranges) or future climates[58,59]. In this study, the niche-only scenarios (A, B and E), combined with exhaustive ground validation, show that our SDMs are very close to representing the fundamental niche, that is, where coffee grows and is farmed. Our niche and forest (migration) scenarios (C, D and F; Supplementary Fig. 5) preserve the relationship to the fundamental niche; applying the humid forest mask also means that we are closer to the realised niche than using an SDM alone.

SDM—division into climatic groups. After running preliminary models for the present day, investigating climate profiles, and considering the biology of Arabica coffee in Ethiopia, it became clear that we should treat east and west of the Rift Valley (Fig. 1) separately. The rainfall pattern east of the Rift Valley is bimodal, and in the west it is unimodal (see Supplementary Fig. 4). Molecular[60–62], morphological[63] and physiological data[64] support Arabica coffee differentiation either side of the Rift Valley. Thus, for our modelling, we treated east and west independently, running the models for each and combining only at the end of the procedure to provide final modelling outputs.

SDM—selection of environmental variables. We examined the full BIOCLIM dataset[34] of 19 variables, independently, east and west of the Rift Valley. Paired dataset correlations and boxed plots were reviewed and we examined which variables had significant influence on the Generalised Linear Models (GLM) and Generalized Additive Models (see below). For each BIOCLIM variable, we ran an analysis of variance (ANOVA) test by examining output model results for our validation points and comparing these to the pseudo-absence points. We also ran models using random pairs of variables to investigate the best variables for model fit (see below). Finally, we examined the resultant BIOCLIM variables and reduced the selection to those that were significant in the above tests, not highly correlated (as pairs) and which represented the ecological requirements of Arabica coffee. By comparing the results independently for east and west of the Rift Valley, we reduced the 19 BIOCLIM variables to nine (Supplementary Table 4), for use in our modelling. The same variables were used for the east and west split, to allow our models to be comparable.

SDM—processing. Using the selected environmental variables (see above), we ran the data (381 ground points) in the Biomod2 R package, version 3.1–64 (ref. 65), using six modelling methods (GLM, Generalized Boosted Regression Models, Generalized Additive Models, Multiple Adaptive Regression Splines (MARS), Random Forest and Maximum Entropy (Maxent) software version 3.3.3 (refs 65–68) to produce an ensemble model for either side of the Rift Valley. Each of the models

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used the nine selected environment variables to maximise its fit to the output prediction. We largely followed established methodologies[65,69–71] for model evaluation, runs, replications and combination. We used the default setting in Biomod2, except for increasing the number of iterations for GLM and Maxent, to reach convergence. Three sets of background or pseudo-absence data were generated. Ground control data, both presence and background for each of the three sets, was split randomly ten times with a ratio of 70:30 to build training and testing data, respectively[72]. Model outputs from Biomod2 were evaluated by viewing the actual results and using sensitivity, specificity, True Skills Statistics (TSS), Cohen's Kappa statistic (KAPPA) and relative operating characteristic curve for east and west of the Rift Valley models (see Supplementary Information). Following Araujo & New[70] and Thuiller *et al.*[69,71] we took the six individual models to produce an ensemble prediction for either side of the Rift Valley, using the suggested model evolution threshold of 0.7 (using TSS), to remove poorly performing models (although no models were removed during this process, as they all exceeded this threshold). We also implemented proportional weighted overlay, to give better fitting models a higher weight. During the statistical evaluation of the six models, expert review was used to make sure that they were in agreement with the biotic and abiotic requirements for Arabica coffee. The testing and training data were assessed and reviewed to give the relative importance of the variables used in each developed model, model sensitivity and specificity, as well as overall model performance[72]. All six niche model methods performed exceptionally well (over 90% for specificity and sensitivity for each model).

There are two assumptions associated with the models for 1960–1990: (1) because the 2014 TRF/MAF[6] forest cover (see Supplementary Fig. 6) was used with 1960–1990 data, the surface area will be underestimated, as there has been considerable deforestation since the 1960s[5]; and (2) we assume that the suitable coffee niche, if forested or having sufficient shade cover, is being used for coffee production of some description[25].

SDM—evaluation. Model outputs from Biomod2 (ref. 65) were evaluated by viewing the resultant maps and using the statistics; sensitivity, specificity, TSS, KAPPA and relative operating characteristic curve for east and west of the Rift Valley. For our purposes, sensitivity and specificity was the most useful and easiest to use metric, but we reviewed all statistics. All six niche model methods performed very well (over 90% for specificity and sensitivity), but east of the Rift Valley showed slightly lower specificity values, compared to west (this is not surprising as the sample for the east is much smaller). GLM and MARS showed the lowest scores (90–93% for GLM and MARS for specificity), which is still very good, but suggests they are not fitting the data as well as other models. Final models were produced from ten runs and three replicates. We checked the outputs visually to see if there was a noticeable difference between model runs (which may suggest problems, for example, overfitting or incorrect models).

SDM and WorldClim—validation. The ensemble SDM was loaded onto four large-format, GPS-enabled mobile phones (Samsung Note II, GT-N7100), using Locus Map Pro 3.1, Asamm Software, Praha, for validation during seven fieldwork trips (2015 to 2016). This activity revealed excellent correspondence between the ensemble SDM and coffee farming areas; the SDM predicted coffee farming activity to within a 1 km radius of each validation location.

As a means of checking the WorldClim[34] precipitation data, we compared precipitation data from 27 weather stations over a 30-year period (1984–2014) (National Meteorology Agency Ethiopia) against the WorldClim[34] data (1960–1990). We found acceptable to excellent agreement between the two data sets, when visualized as c. 30 year averages for numerous locations. Climate profiles (30-year period; 1984–2014) for total monthly rainfall and average monthly temperature (minimum, median and maximum) for an additional 20 weather stations (National Meteorology Agency) situated within, or adjacent to, coffee growing areas, were also found to be in good agreement with 1960–1990 WorldClim[34] data. Six examples are provided in Supplementary Fig. 4. At Yayu (Illubabor), Ashi (Wellega), Gesha (Bench-Maji), Yirgacheffe and Yirga Alem (Sidamo), Bale (Bale) and Gololocha (Arsi) (see Fig. 1) we installed (2013–2016) proprietary data-logging equipment (Tinytag Plus 2—TGP-4500, with Stevenson type screen (ACS-5050), both from Gemini Data Loggers), to measure air temperature and relative humidity (RH%). At Ashi, Gesha and Bale we also installed soil temperature probes (Tinytag Plus 2—TGP-4510, Gemini Data Loggers), soil moisture (10HS) and soil water potential sensors (MPS-6) connected to EM50 digital data loggers (all from Decagon Devices) at 20 and 40 cm soil depths and low resolution rain gauges (ECRN-50, Decagon Devices). The logging interval was every hour on the hour for Tinytag Plus 2 and twice daily for the Decagon equipment. The data was not analysed for this study, but simply used to ground-truth WorldClim[34] data and the coffee niche and to better understand the climatic variables causing physiological stress in coffee.

SDM—assessment of climatic variables. We examined the BIOCLIM[34] data to see which bioclimatic variables were contributing most to the SDMs, by summarizing the contribution of each variable for each of the six niche modelling methods (Supplementary Table 2 and 3), for east and west of the Rift Valley. For the east, the most important were temperature seasonality (BIO4) and precipitation of the warmest quarter (BIO18); and the west, annual mean temperature (BIO1) and annual precipitation (BIO12).

Selection of GCMs. The evaluation and selection of GCMs for a study area and set of circumstances is a challenging activity[24,73,74]. Ideally, we would have used all GCMs to assess the full range of outcomes, but selected three in order to keep processing time and storage to a manageable level and to reduce redundancy (for example, where GCMs were in agreement). To make our selection, we processed all 23 GCMs available for the study area, excluding models that did not fit our future time periods (2010–2039, 2040–2069 and 2070–2099). We then reviewed the projections for each of the contributing BIOCLIM layers, for eight coffee locations either side of the Rift Valley, as a representative sample of the of the coffee farming landscape: for the South West Zone (Yayu (Illubabor), Dembi Dollo and Ashi (Wellega)); South East Zone (Bale (two sub-locations), Yirgacheffe and Yirga Alem (Sidamo)); and Harar Zone (Gololocha (Arsi)); an example for one of these locations (Ashi) is shown in Supplementary Fig. 15. On reviewing these graphs, we rejected GCMs that were highly anomalous for temperatures and anomalously high or low values for precipitation; an emphasis was placed on the 2010–2039 period, where anomalies are more easily assessed. We selected a representative GCM for those showing similar results across the nine BIOCLIMs, two emission scenarios and four time intervals. This still left us with eleven GCMs from which we choose three (BCCR-BCM2.0, CSIRO-MK3.5 and GFDL-CM2.1) to represent climatic changes over time (for the subset of 11 GCMs; across the nine BIOCLIMs).

GCM data downscaling. The original ground resolution for the GCMs was approximately 200 km. To make this data more useful for SDM and to see variation at higher resolutions, we used downscaled GCMs[34,75,76]. We employed the downscaled (Delta method of the Intergovernmental Panel on Climate Change (IPCC) AR4 (ref. 76)) climate models from CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) (http://ccafs-climate.org/data_spatial_downscaling/ and http://www.ccafs-climate.org/data/). The downscaled method used by CCAFS is based on thin plate spline interpolations of deltas (anomalies) of the original low-resolution GCM outputs. These deltas are applied to the WorldClim[34] data (the same data we used for our 1960–1990 SDM) at a resolution of 30 arc seconds (approximately 1 km^2 cells size for Ethiopia) by interpolating between GCM cell centroids[76]. The 19 bioclimatic indices (BIOCLIM)[77] were calculated by CCAFS from the resultant rasters.

GCMs—modelling future projections. Our three selected GCMs were: (1) BCCR-BCM2.0—BCCR, Univ. of Bergen, Norway (BCM Version 2); (2) CSIRO-MK3.5—Centre for Australian Weather and Climate Research (Mark 3.5); and (3) GFDL-CM2.1—GFDL USA (Coupled Climate Model 2.1). The future SDM variability of the selected GCMs is illustrated in Figs 2 and 3. We used two CO_2 emission scenarios, A1B and A2: A1B reaching 13.5 giga tonnes of carbon (GtC) by 2099; and A2 reaching 29.1 GtC; this is against a baseline of 9.8 GtC (in 2014/15). The projections (areas of coffee-growing suitability given as percentages and km^2) produced from the three GCMs were categorised into three classes: low, middle and high (Table 1). For the Results and Discussion, we provide percentages and area measurements (km^2) for the middle-range outcome, based on the three GCMs (Table 1; Supplementary Table 1). The GCM CSIRO-MK3.5 predominately produced the middle-range outcomes; BCCR-BCM2.0 tended to produce low-range outcomes and GFDL-CM2.1 the higher ones, although these switched between low, middle and high, depending on the suitability category and time intervals across this century.

The future projections were modelled in the Biomod2 package Ensemble Forecasting[65], which projects the ensemble recent past and current model in space and time. The projection was performed on the nine BIOCLIM variables as identified above. Future models were run for each GCM, for east and west of the Rift Valley and over three time periods (2010–2039, 2040–2069 and 2070–2099; Supplementary Fig. 1), giving 18 future projections (two regions, over three dates and three GCMs) as a final output.

Combining SDMs and GCMs—analysis and mapping. The outputs from the four time periods (1960–1990, 2010–2039, 2040–2069 and 2070–2099) were imported into ArcGIS ver. 10.1 (Esri), with the spatial analysis extension, for further analysis and visualization. The Rift Valley separation, from each modelling stage, was combined using the raster calculator tool to give the maximum suitability value for each pixel, giving 19 models for the final analysis (one time period (1960–1990) plus three GCMs × two emission scenarios, across three further time periods). To visualise the SDM variability, the projections were processed to show the range of SDM values and these ranges were categorised into three classes: (1) Very Strong, model variability 0 to 200; (2) Strong, 200 to 400; and (3) Weaker, 600 or higher. Very strong (solid colours, with no overlay) shows where the model class (Excellent, Good, Fair, Marginal and Unsuitable) is unlikely to change, except at the edge of the ranges. Strong (overlaid with dots) shows where a class could change up or down by one class (for example, Good could range from Excellent to Fair). The Weaker class (diagonal lines) is where classes could change by more than one class; the largest range is 610, indicating a movement of up to one and a half classes. We adopted the same symbology as used in a widely read IPCC report[22], although it should be noted that we used it for SDM variation not GCM variation (as in the IPCC report). We

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also calculated the median for each model, which was used only for visualization of the results (Figs 2 and 3).

Categorisation of projection maps. To provide area measurements (in km^2) for each category (Unsuitable, Marginal, Fair, Good, Excellent), we needed to threshold the continuous SDM values (those between 0 and 1,000). To achieve this, we examined the SDM values for our ground point data (ground control, absence and pseudo absences data), by comparing TSS and the cumulative percentage of points to give us our initial threshold. This was further subdivided to give a total of five categories (Supplementary Fig. 2; Supplementary Information).

Migration scenarios for climate change projections. The six migration scenarios (Box 1; Supplementary Fig. 5) were processed in ArcGIS, using simple map algebra, summarized, with the following processing: (A) no processing; (B) all models cookie-cut with 1960–1990 suitable niche (all areas outside of the 1960–1990 niche were clipped for all dates); (C) as A but cookie-cut with forest cover; (D) as B but cookie-cut with forest cover; (E) as B but 2040–2069 cookie-cut with 2010–2039 suitable niche and 2070–2099 cookie-cut with 2010–2039 and 2040–2069 suitable niche; (F) as E but additionally cookie-cut with forest cover. The forest cover niche models were resampled at 30 m resolution using a simple nearest-neighbour resampling (to preserve the original model resolution of 1 km^2).

Analysis of regional trends and drivers. To understand the trends and the main drivers for climate change outcomes we produced graphs of change for the most influential BIOCLIMs. Supplementary Figs 9–12 show the trends for each of the five coffee zones (Fig. 1), from 1960–1990 to 2070–2099. The most influential BIOCLIMs were: temperature seasonality (BIO4), precipitation of the warmest quarter (BIO18), annual mean temperature (BIO1) and annual precipitation (BIO12). We calculated the mean, max, min and range for each zone, for CMIP3 scenarios A1B and A2, the three GCMs and all four date periods.

CMIP3 versus CMIP5. Our projections are based on the WCRP's CMIP3 multi-model dataset[37]. The newer and more developed WCRP CMIP5 multi-model ensemble[38] was released as a downscaled dataset after the project research period. A direct comparison between CMIP3 and CMIP5 is not straightforward, as CMIP3 uses emission scenarios, whereas CMIP5 uses RCPs[39]. Following the methods of Knutti & Sedláček[39], we compared CMIP5 RCP8.5 against CMIP3 SRES scenario A2, which represents the two scenarios with the highest temperature changes. Supplementary Figs 15 and 16 show a comparison of the GCM robustness across Africa for CMIP5 (RCP8.5) vs CMIP3 (SRES A2) based on Knutti & Sedláček[39]. For further comparison, we included CMIP5 RCP8.5 in the same analysis that we used to represent the five coffee zones (Fig. 1) for CMIP3 A1B and A2 (Supplementary Figs 9–12). Both the GCM and the downscaling methods (Delta method[76] IPCC AR4[78] to Delta method IPCC AR5 (ref. 79)) were updated when moving from CMIP3 to CMIP5. Where possible, we used the most up to date version of each GCM: GFDC-CM2.1 and CSIRO-MK3.5 for CMIP3 scenarios A2 and A1B were updated to GFDL-CM3 and CSIRO-MK3.5 for the CMIP5 scenarios, respectively. There was no updated GCM for BCCR-BCM2.0, so we used BCCR-CSM1.1m to give us an output level for comparative purposes. The period 2010–2039 was not available for CMIP5, so we substituted the period 2020–2049.

Data availability. The data that supports the findings of this study are available from the corresponding author upon request. The supply of ground point data is restricted, as ownership is shared across the authorship and externally.

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Author contributions

J.M. and A.P.D. conceived and led the study; A.P.D. and J.M. led the project; all authors collected data; J.M., A.P.D., J.W., S.B. and T.W. analysed and processed the data. J.M. and A.P.D. wrote the paper with contributions from all authors.

Additional information

Supplementary information is available for this paper.

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Competing interests

The authors declare no competing financial interests.

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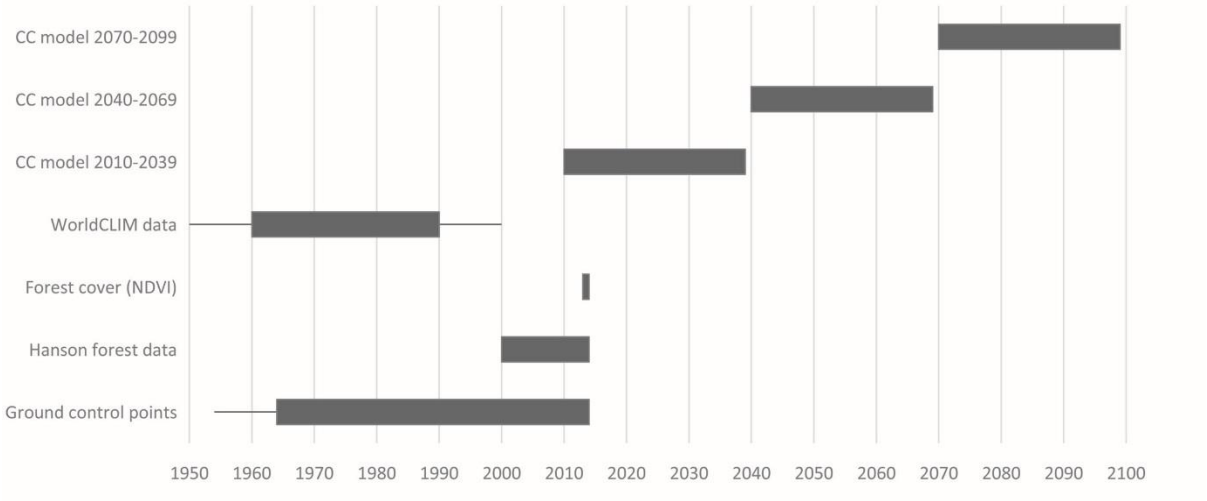
Resilience potential of the Ethiopian coffee sector under climate change

Justin Moat[1,2]*, Jenny Williams[1], Susana Baena[1,2], Timothy Wilkinson[1], Tadesse W. Gole[3], Zeleke K. Challa[3], Sebsebe Demissew[1,4] and Aaron P. Davis[1]*

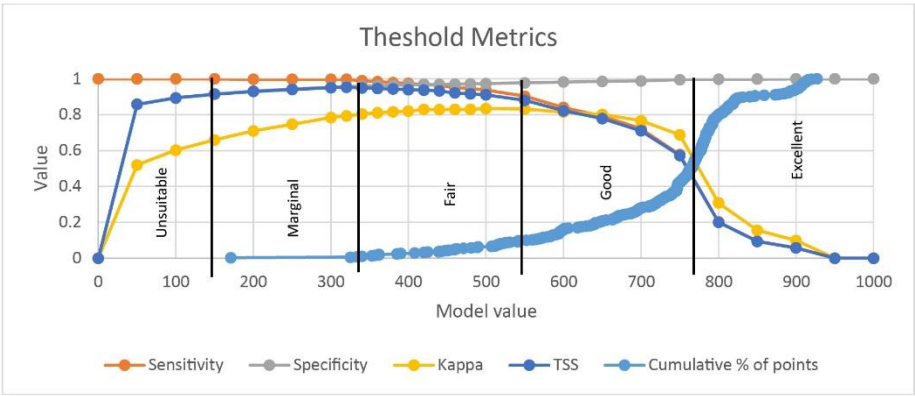
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SUPPLEMENTARY FIGURES



Supplementary Figure 1.Date ranges for study datasets. Whiskers represent limited data availability in that period. Note. CC model = climate change model.



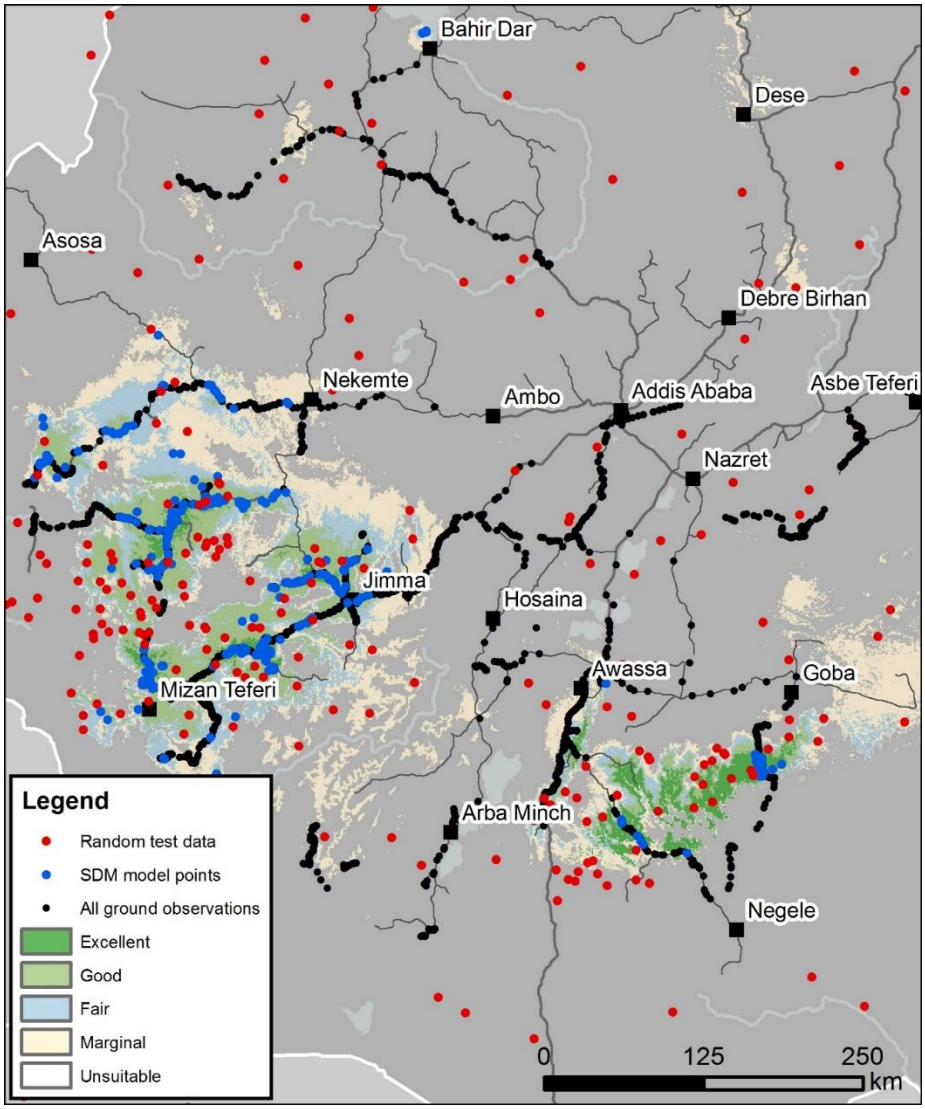
Supplementary Figure 2. Graphs of five threshold statistics vs. model values. See Box 1A for explanation of environmental niche (coffee suitability) categories (Unsuitable, Marginal, Fair, Good and Excellent). Thresholded values and statistics used for SDM classification. Y value = threshold statistic value, X = SDM model value (from 0 unsuitable to 1000 excellent). Actual categories used for cut offs are highlighted with vertical black lines. Threshold metrics for categorising model suitability (statistic with maximum model threshold values in parentheses): Kappa (504); True skills static TSS (324); Sensitivity=Specificity (424); accumulative percentage of ground observation points 100% (177); 99% (353); 95% (462); 90% (552); 65% (737); 50% (764); 35% (780); 25% (792); 10% (840); 5% (904); 1% (914).

Notes for Supplementary Figure 2.

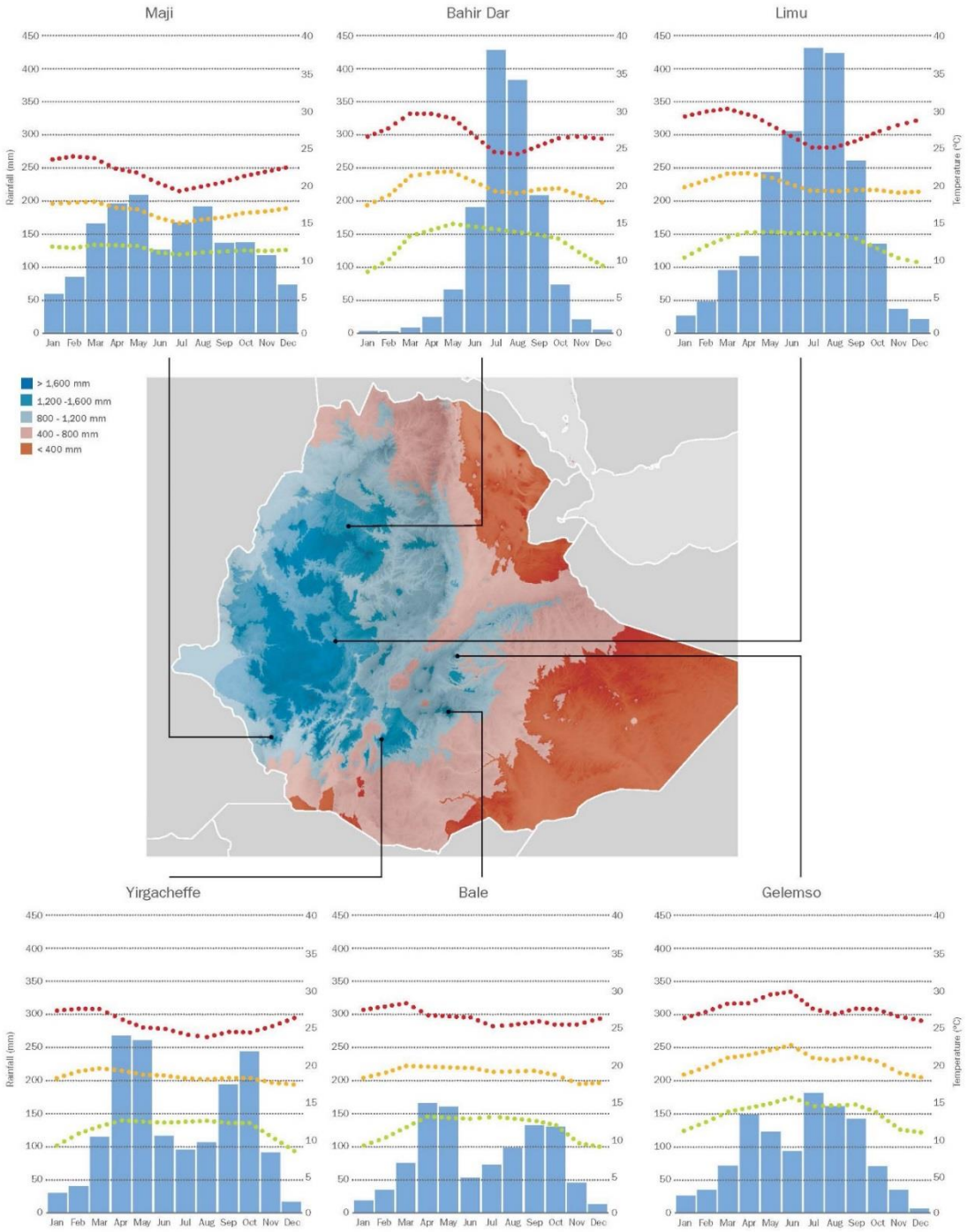
To allow the data to be easily presented and analysed we needed to categorise the SDM values. To do this we examined and calculated various thresholds as normally applied to SDMs.This was calculated using the ground-data localities (east and west of the Rift Valley) and the pseudo absences produced as part of the Biomod2 model development. We calculated Kappa coefficient, TSS, balance of sensitivity and specificity as well as accumulative thresholds of; 99%, 95%, 92%, 65%, 35% and 10% of the ground data point localities.

For the bottom threshold we chose 99% (353 ground data points) as this is a conservative balance between all the thresholds (Kappa 504, specificity=sensitivity 424, 99% 353 points and TSS 324 points), which resulted in losing only four ground control points. Not all values are able to fit all the models, for a number of reasons: there are no variables in the model to describe the specific ground-data locality points; we do not have the resolution to describe these localities or the local conditions are not represented (e.g. ground water, microclimate).

The upper thresholds are used for descriptive purpose only. From the histogram we can see that there are many localities (ground-data points) from 750 to 840, and so it would seem prudent to add a boundary here (35% of ground-data points (780)). To give a differentiation at the lower limits (between 353 and 780 ground-data points) the third threshold was set at 550, giving thresholds at 353,550, and 780. We have also placed a lower threshold at 171, and although it is a relatively artificial boundary, it does correspond with our lowest test locality (and is approximately between our lowest modelled value of 7 and our threshold 353). This allows us to see changes in the lower predicted categories.



Supplementary Figure 3. Ground control and test points used in this study overlaid on suitable niche. Black dots = all ground observations (3070 points), including coffee, non-coffee, cultivation, historic collects etc.; blue dots = final points used to produce models (381 points of the original 3070); red dots = random test locations (150 in forest/SDM and 150 outside), used to independently test accuracy of forest cover and SDM.



Supplementary Figure 4. Annual rainfall map of Ethiopia (background) and charts of rainfall (blue bars) and temperature (red maximum, average orange, green minimum) profiles for six coffee growing locations (present day). Bi-modal rainfall pattern (east of Rift Valley: Yirgacheffe, Bale and Gelemso); uni-modal rainfall (west of Rift Valley: Maji [slight rainfall bi-modality], Bahir Dar and Limu). Graphs based on historical climate data (30 year averages 1960–1990) from WorldClim[1], verified for accuracy using weather station data (30 year averages), for Bahir Dar, Limu, Yirgacheffe, and Gelemso. Background annual rainfall map of Ethiopia also from WorldClim[1].

Notes for Supplementary Figure 4

Bahir Dar. Sufficient annual rainfall, but the dry season (October to February/March) is too long and too dry and coincides with highest temperatures. The bulk of the rain falls in the main wet season (May/June to September). Coffee suitability is Marginal (coffee growing possible but often problematic, with poor and very inconsistent yields) and is often negatively influenced by drought during the dry season.

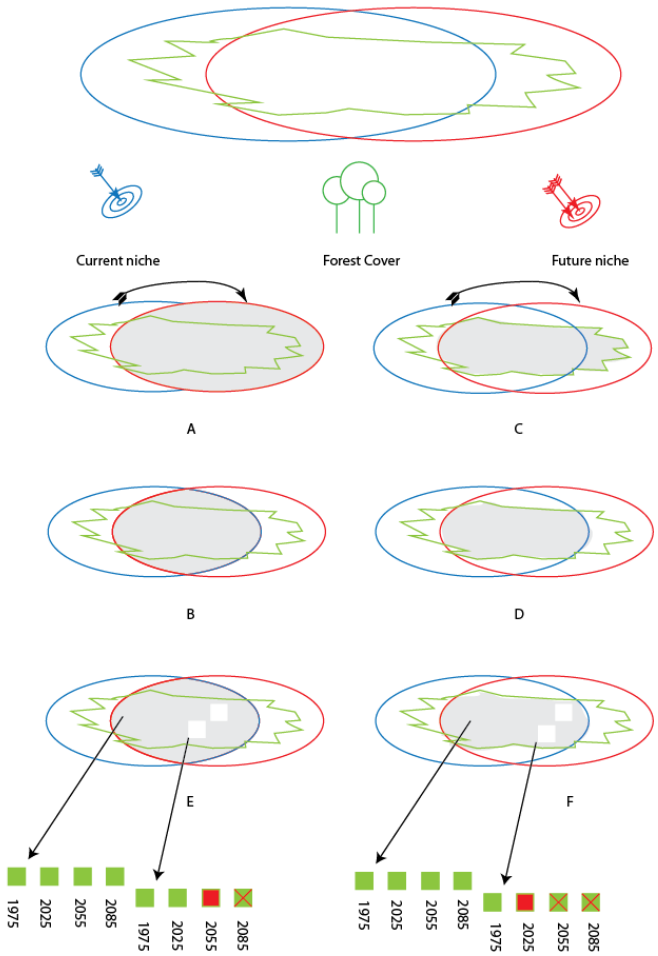
Limu. Sufficient rain throughout the dry season (October to February), and good rains in main wet season (May/June to September). Highest temperatures coincide with sufficient rainfall. Coffee suitability is Excellent (coffee production good to excellent, with the potential for consistent, high quality yields).

Maji. Sufficient rain throughout the dry season (October to February), and good rains in the main wet season (May/June to September). Highest temperatures coincide with sufficient rainfall. Slight bimodality to main season rainfall pattern. Coffee suitability is Excellent (coffee production good to excellent, with the potential for consistent, high quality yields).

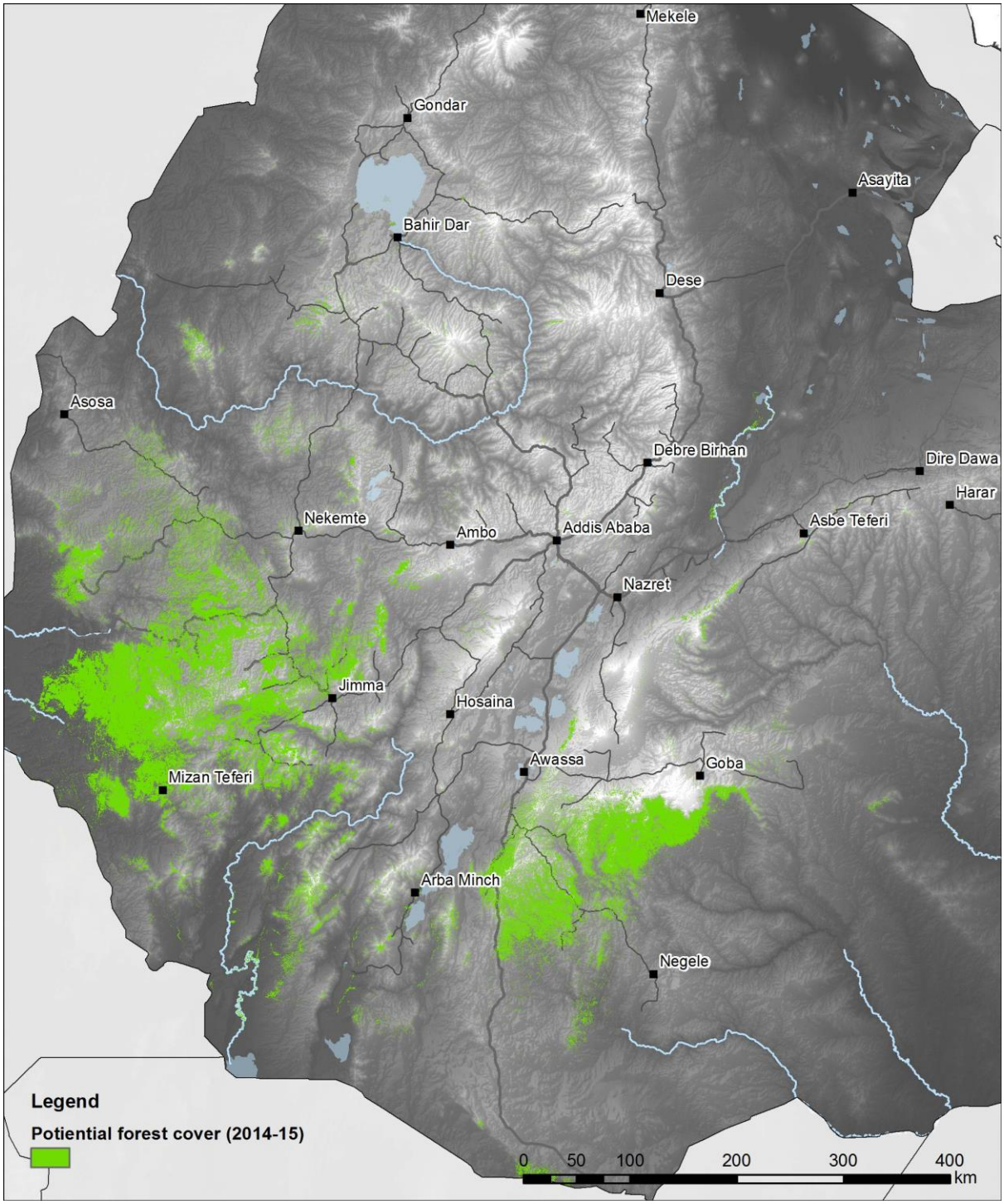
Gelemso. Barely sufficient rain throughout the dry season (October to February), and low rainfall in the main wet season(s) (April to September). Highest temperatures may not always coincide with sufficient rainfall. Coffee suitability is Unsuitable to Marginal (coffee growing is possible but often problematic, with poor and inconsistent yields), especially without intervention (e.g. irrigation).

Bale. Barely sufficient rain throughout the dry season (October to February), and low rainfall in the main wet season(s) (April to September); low rainfall is somewhat offset by lower temperatures. Coffee suitability is Good to Excellent (with the potential for consistent, high quality yields). Yield and quality may be negatively affected in some years (during adverse weather conditions, especially low rainfall).

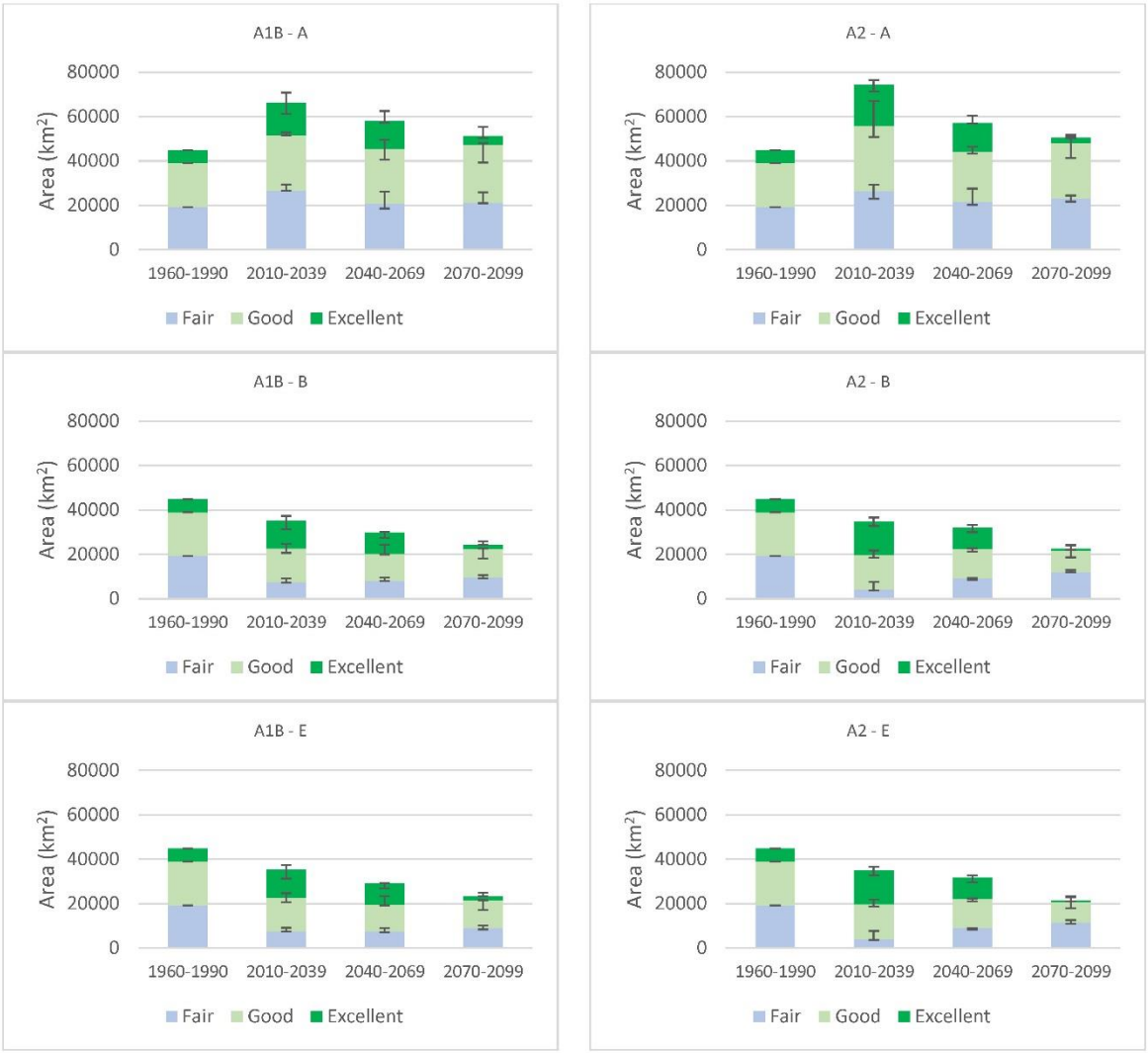
Yirgacheffe. Sufficient rain throughout the dry season (November to February), and sufficient rainfall in the main (and slightly extended) wet season(s) (April to October). Highest temperatures usually coincide with sufficient rainfall. Coffee suitability is Good to Excellent, with the potential for consistent, high quality yields. Yield and quality may be negatively affected in some years (during adverse weather conditions, especially low rainfall).



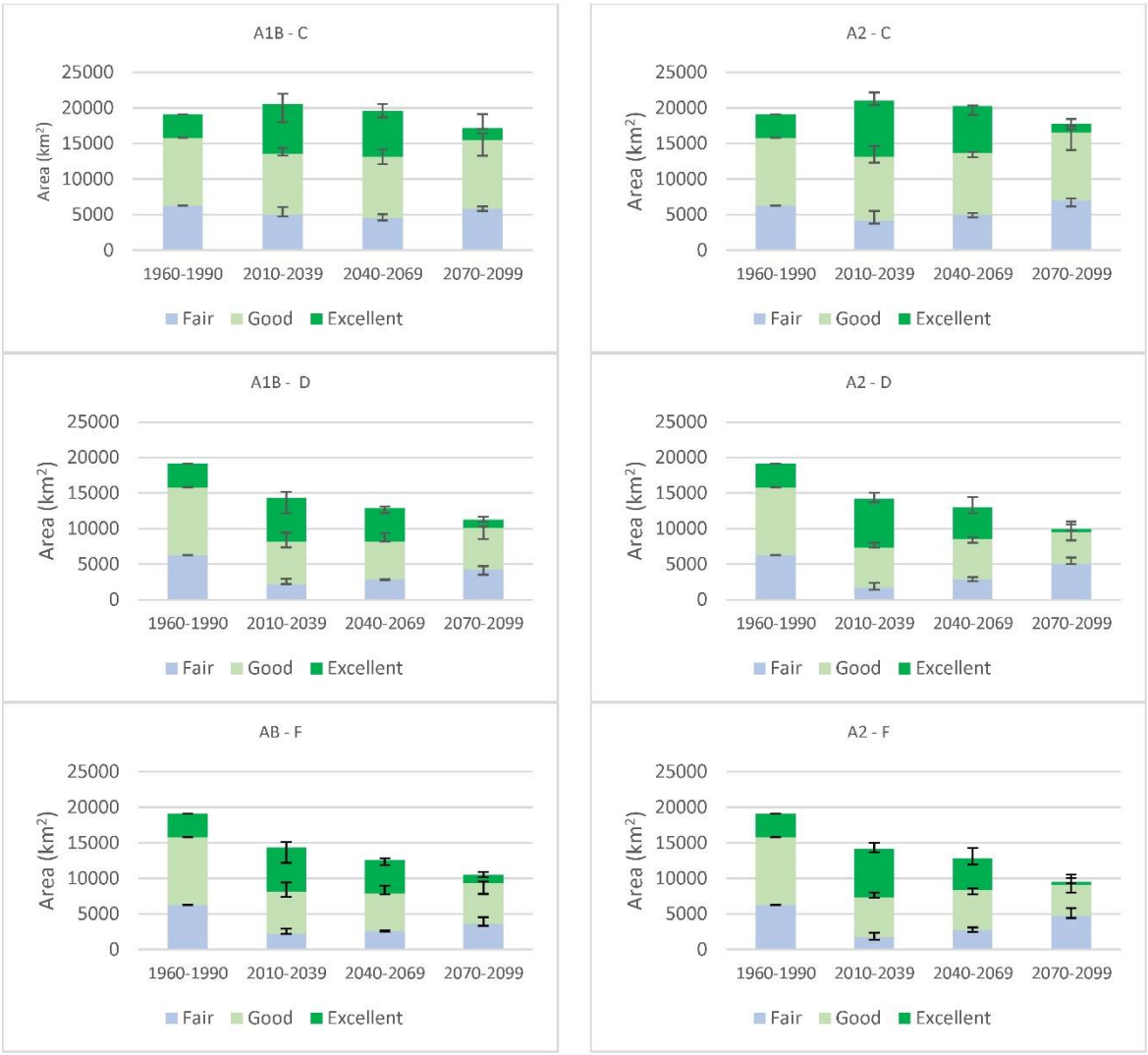
Supplementary Figure 5. Diagram for six future migration scenarios for Ethiopia coffee (farmed and wild), as used in the modelling. A, Plants can grow in any suitable niche (i.e. can move anywhere) [**Full Migration (A)**]. **B,** Plants can only grow only within known niche (i.e. can only move within presently predicted niche). **C,** Plants can only grow within suitable forest cover, within any suitable niche (i.e. can move within suitable forest). **D,** Plants can only grow within suitable forest cover and only in suitable known niche (i.e. restricted to present-day forest cover and suitable niches) [**No Migration (D)**]. **E,** Plants can only grow within suitable niche but only if niche does not drop outside of suitability during any 30-year time period. **F,** Plants can only grow within suitable forest cover and suitable niche, but only if niche does not drop outside of suitability during any 30-year time period.



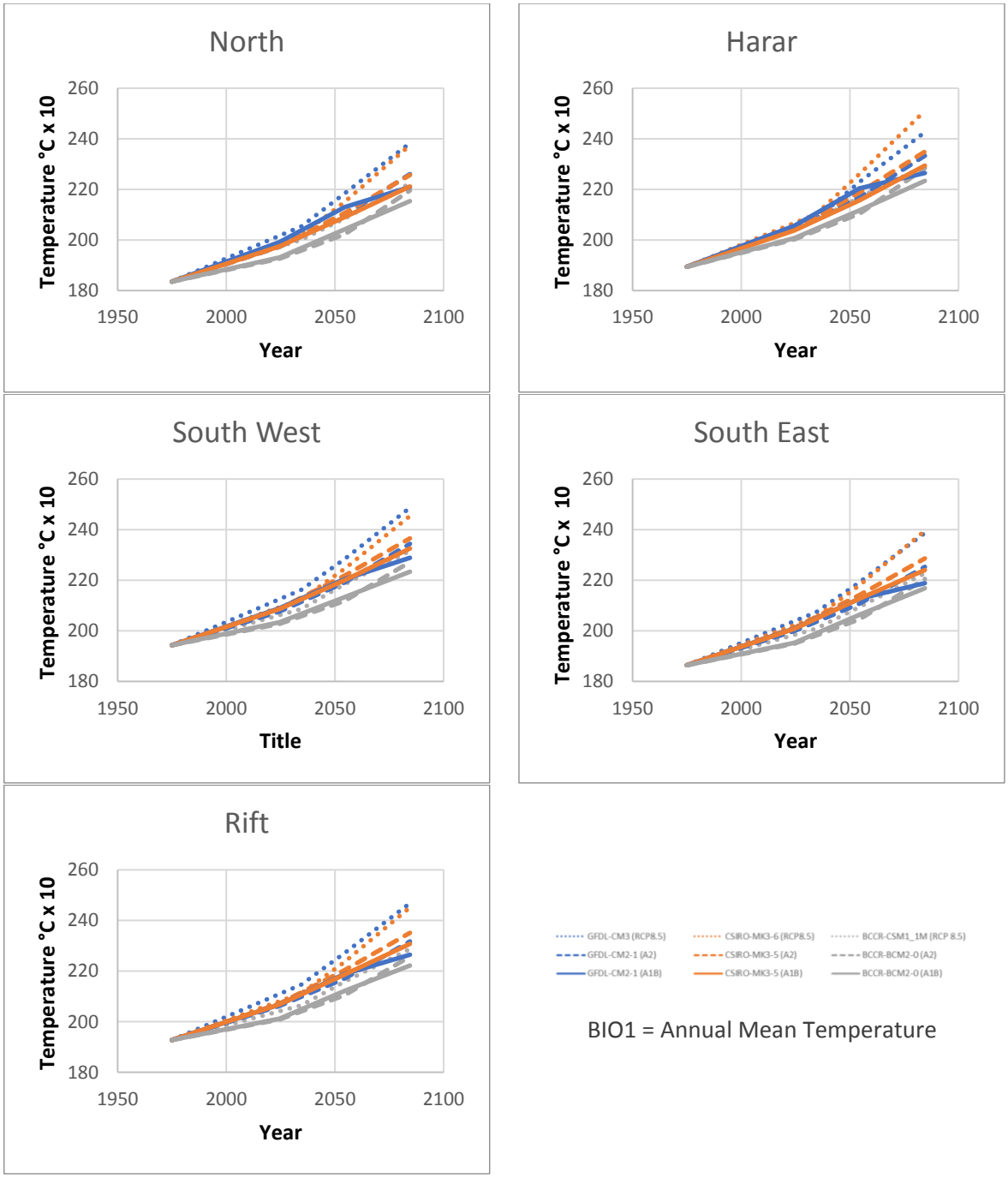
Supplementary Figure 6. Potential humid forest cover (2014–15) derived from Landsat 8 imagery. See Methods for details.



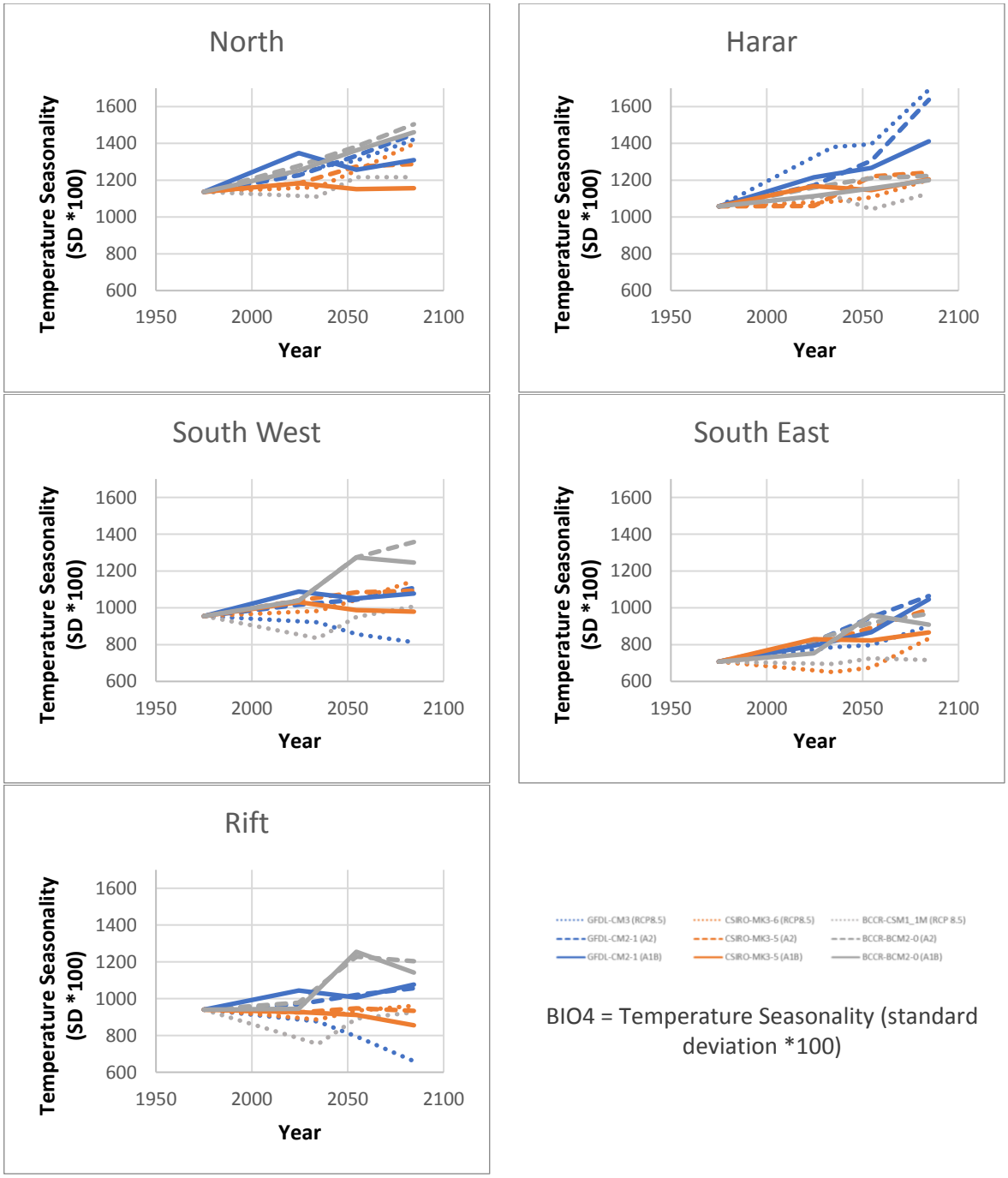
Supplementary Figure 7. **Future prediction for coffee suitability under scenarios A (Full Migration (A)), B, E, across emission scenarios A1B and A2.** Error bars represent the SDM area (km^2) model variability (low and high model outcomes) within the three General Circulation Models (GCMs): GFDL-CM2-1, CSIRO-MK3-5, and BCCR-BCM2-0. See Methods for further details.



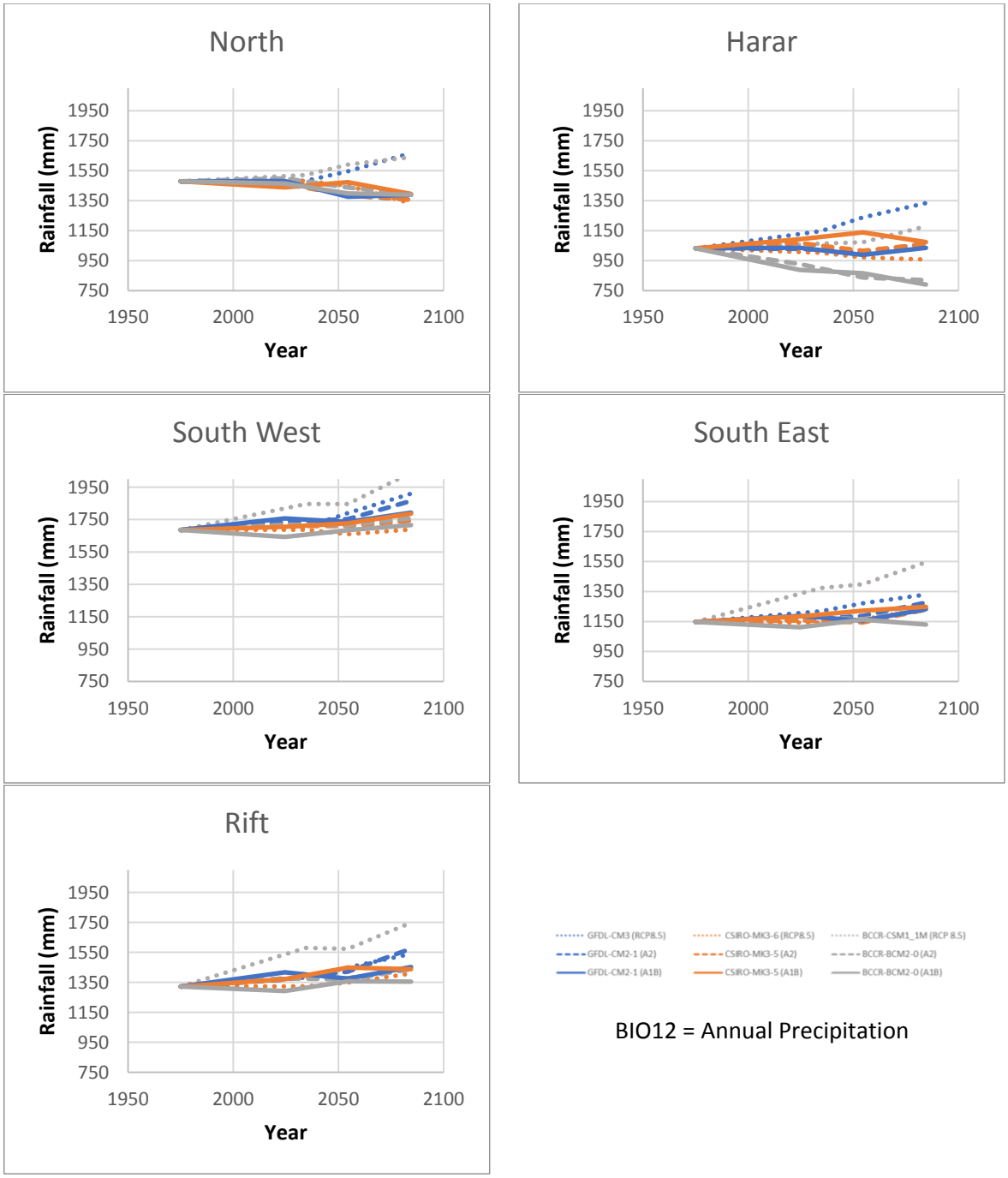
Supplementary Figure 8. Future prediction for coffee suitability under scenarios C, D (No Migration (D)), F, across emission scenarios A1B and A2. Error bars represent the SDM area (km^2) model variability (low and high model outcomes) within the three General Circulation Models (GCMs): GFDL-CM2-1, CSIRO-MK3-5, and BCCR-BCM2-0. See Methods for further details.



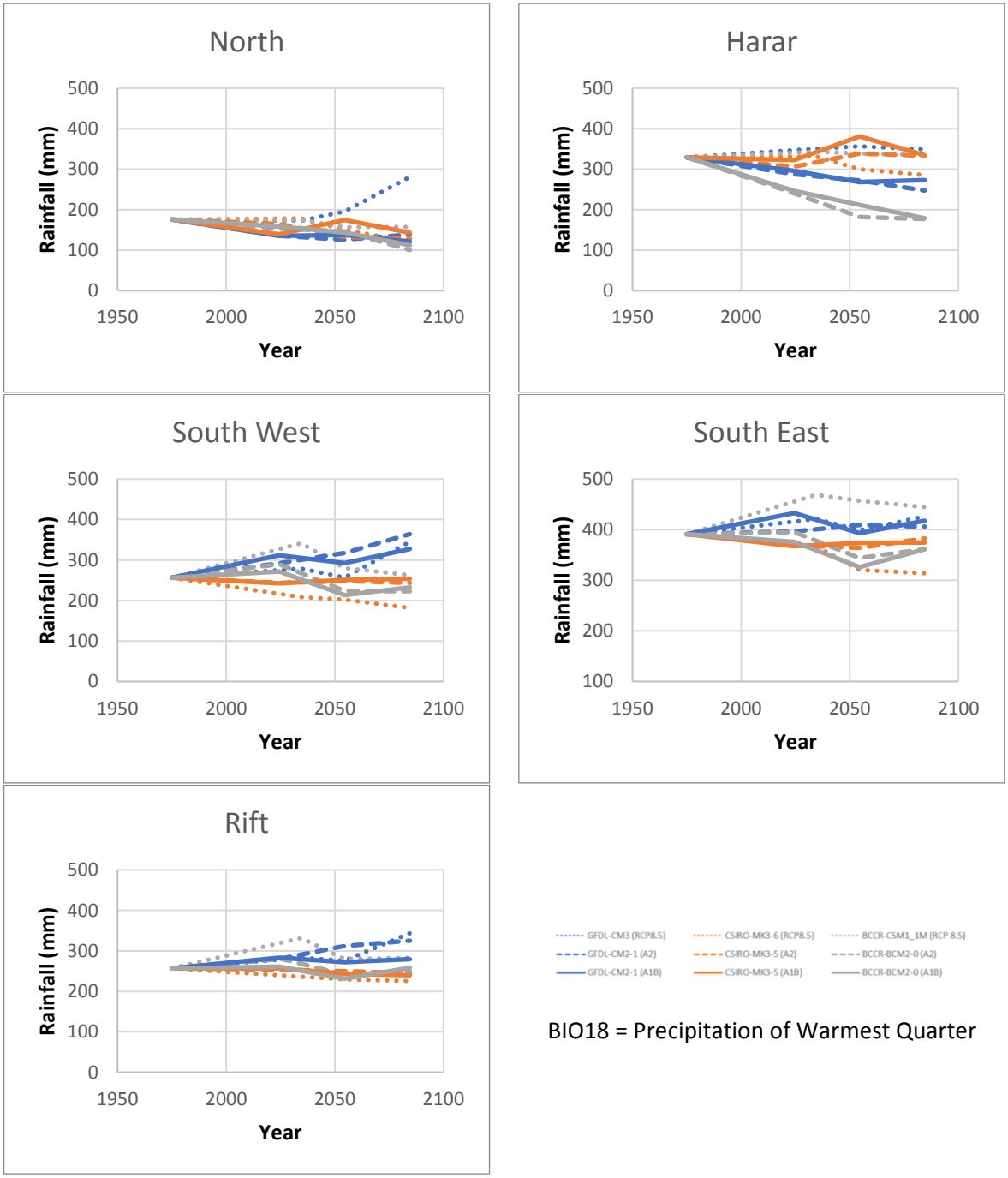
Supplementary Figure 9. Changes in mean annual temperature (BIOCLIM 1). Based on BIOCLIM data[1] (1960–1990), three GCMs, A1B, A2 emission scenario (CMIP3), and RCP 8.5 (CMIP5), for all coffee zones: North, Harar, South East, South West and Rift (see Fig. 1). See Methods for further details.



Supplementary Figure 10. Changes in temperature seasonality (BIOCLIM 4). Based on BIOCLIM data[1] (1960–1990), three GCMs, A1B, A2 emission scenario (CMIP3), and RCP 8.5 (CMIP5), for all coffee zones: North, Harar, South East, South West and Rift (see Fig. 1). See Methods for further details.

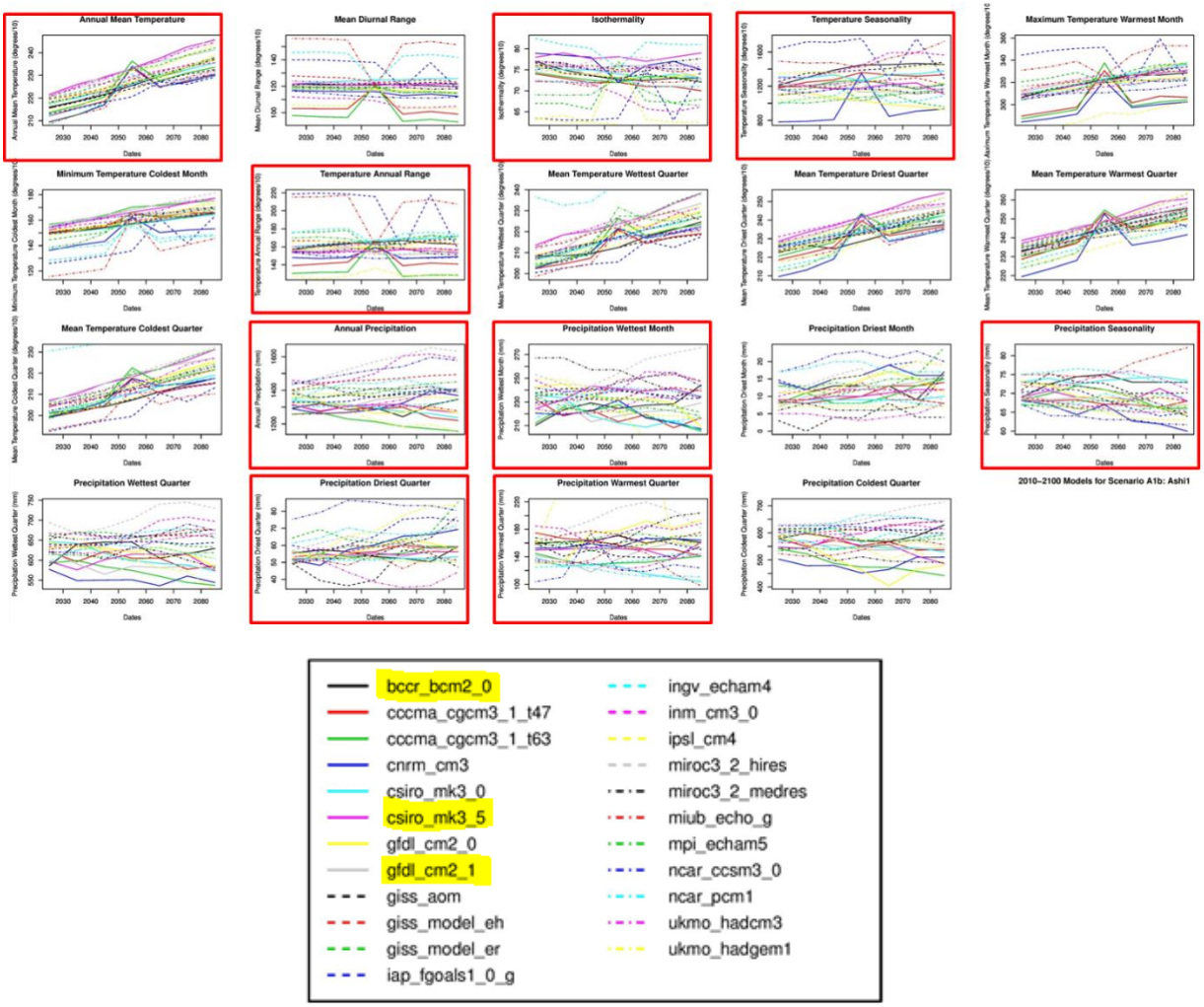


Supplementary Figure 11. Changes in annual precipitation (BIOCLIM 12). Based on BIOCLIM data[1] (1960–1990), three GCMs, A1B, A2 emission scenario (CMIP3), and RCP 8.5 (CMIP5), for all coffee zones: North, Harar, South East, South West and Rift (see Fig. 1). See Methods for further details.

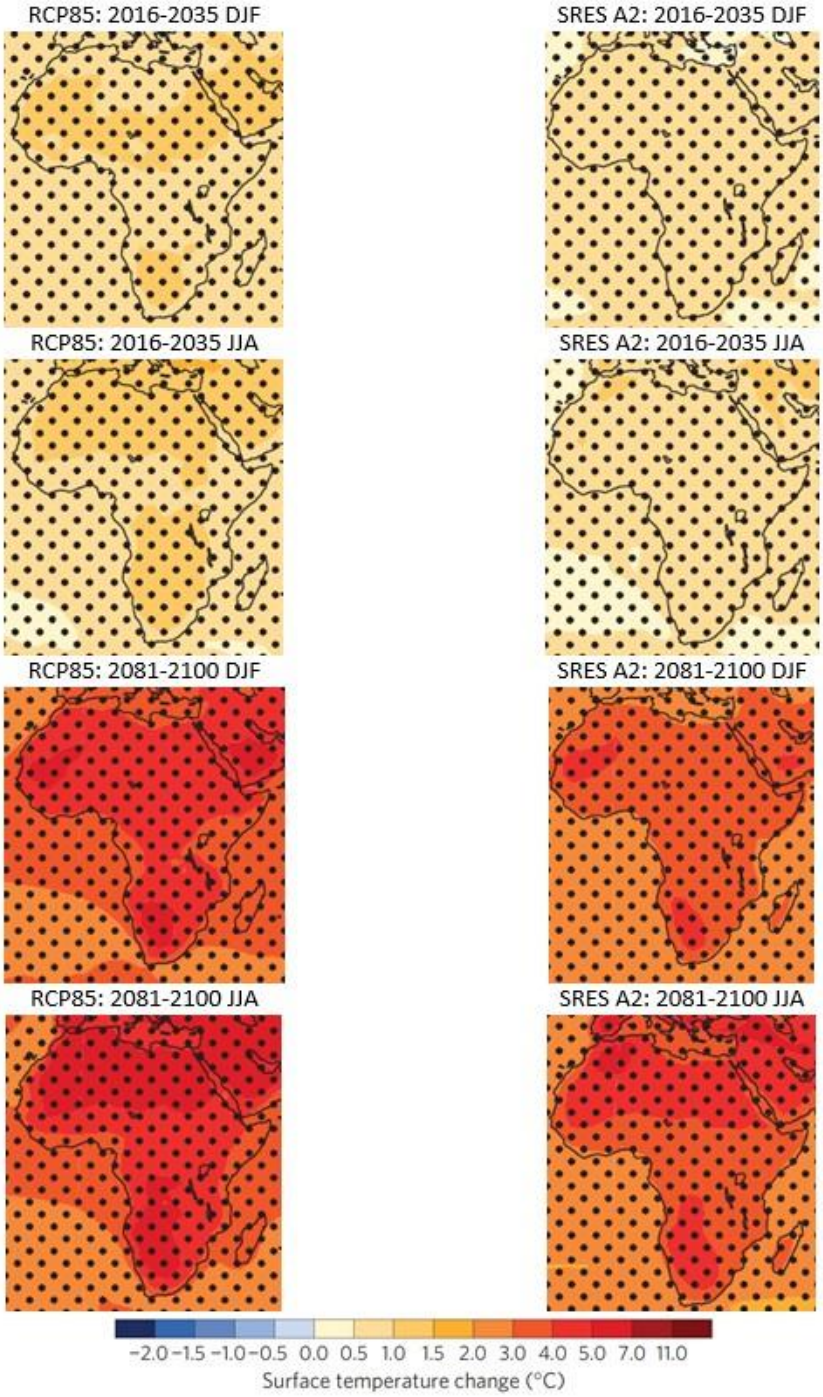


BIO18 = Precipitation of Warmest Quarter

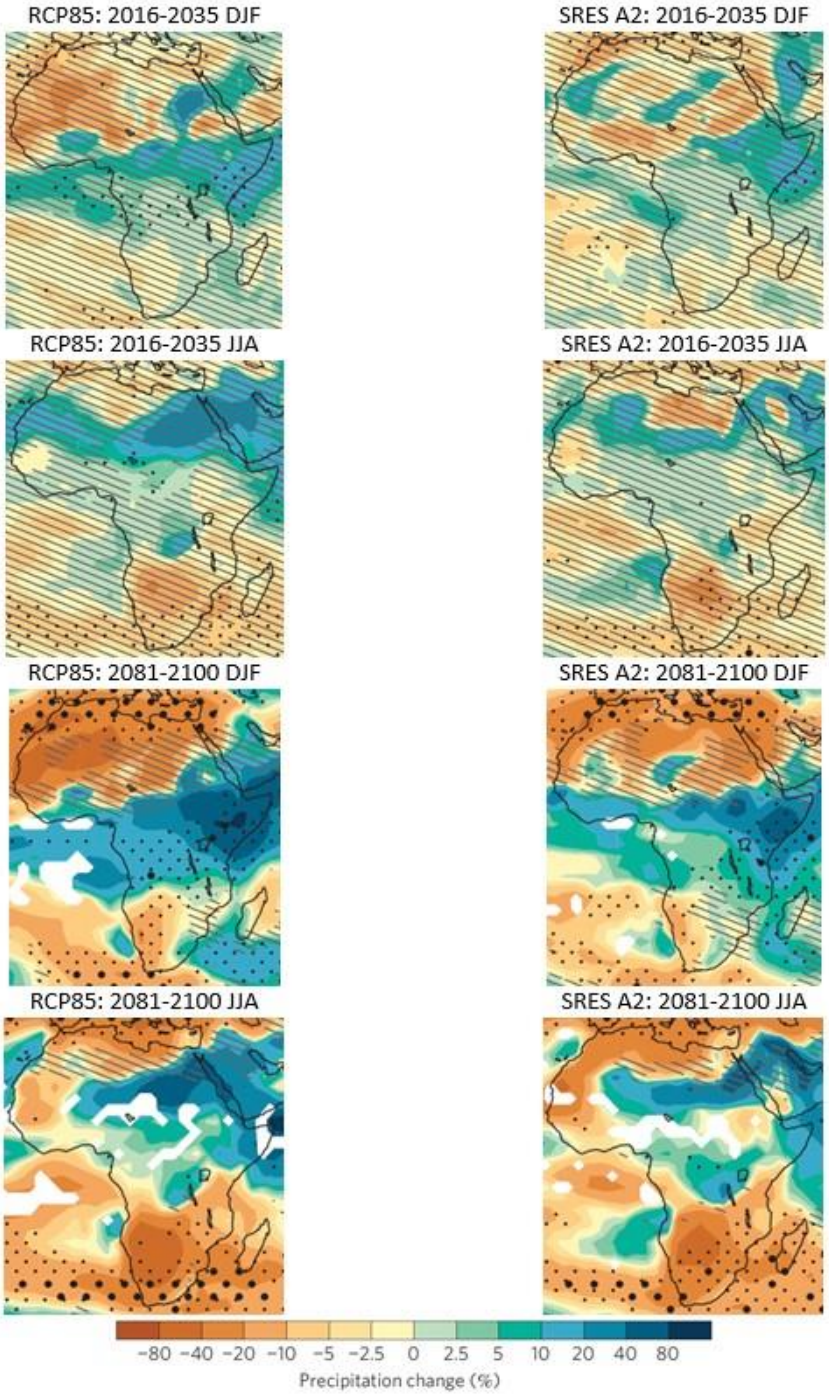
Supplementary Figure 12. Changes in precipitation of the warmest month (BIOCLIM 18). Based on BIOCLIM[1] data (1960–1990), three GCMs, A1B, A2 emission scenario (CMIP3), and RCP 8.5 (CMIP5), for all coffee zones: North, Harar, South East, South West and Rift (see Fig. 1). See Methods for further details.



Supplementary Figure 15. Example of GCM plots used to evaluate GCMs for the coffee landscape of Ethiopia. Plots for Ashi (Wellega coffee area). Highlighted in red are BIOCLIM[1] variables used for our SDMs. Key to GCM (lower box); highlighted in yellow are the three final models used. Mean temperature of the wettest quarter (third from left, second row down) model GCM ingv_echam4 (blue dotted and dashed line), is a good example of a possible erroneous dataset, which show a disjunct of over 2°C from of all other GCMs.



Supplementary Figure 16.Patterns of surface warming for CMIP5 vs CMIP3. Detail of Africa from Knutti and Sedláček Figure 2[2]. Patterns of surface warming. Multi-model mean surface warming for two seasons (December–February, DJF, and June–August, JJA) and two 20-year time periods centred around 2025 and 2090, relative to 1986–2005, for CMIP5 (left) and CMIP3 (right). Stippling marks high robustness, hatching marks no significant change and white areas mark inconsistent model responses.



Supplementary Figure 17.Patterns of precipitation change for CMIP5 vs CMIP3. Detail of Africa from Knutti and Sedláček Figure 3[2]. Patterns of precipitation change. Multi-model mean relative precipitation change for two seasons (December–February, DJF, and June–August, JJA) and two 20-year time periods centred around 2025 and 2090, relative to 1986–2005, for CMIP5 (left) and CMIP3 (right). Stippling marks high robustness, hatching marks no significant change and white areas mark inconsistent model responses.

SUPPLEMENTARY TABLES

Year periods	Migration scenario	Niche categories (km^2)				Total suitability (km^2) for Fair to Excellent – middle value from GCMs
		Marginal	Fair	Good	Excellent	
1960-1990	A	40,386	19,241	19,767	5,812	44,820
2010-2039	A	38,403	26,662	24,911	14,585	66,158
2040-2069	A	38,319	20,663	24,816	12,557	58,036
2070-2099	A	39,648	21,047	26,181	4,052	51,280
1960-1990	D	6,676	6,294	9,536	3,312	19,142
2010-2039	D	999	2,219	5,976	6,123	14,319
2040-2069	D	2,228	2,891	5,306	4,700	12,897
2070-2099	D	3,827	4,284	5,858	1,115	11,256

Supplementary Table 1. Availability of suitable niche in km^2 for Full Migration (A) and No Migration (D) scenarios, generated from the three GCMs, for emission scenario A1B. Only middle values shown (see Table 1 for all values).

Description	MAXENT	GLM	GAM	RT	GBM	MARS	No.in top 3
Annual Mean Temperature = bio_1	0	0.15	0.35	0	0	0.29	0
Isothermality (BIO2/BIO7) (* 100) = bio_3	0.05	0.12	0.24	0	0	0.04	0
Temperature Seasonality (standard deviation *100) = bio_4	**0.56**	**0.74**	**0.77**	**0.22**	**0.23**	**0.2**	**6**
Temperature Annual Range (BIO5–BIO6) = bio_7	0.31	0.38	0.41	0.04	0.01	0.08	2
Annual Precipitation = bio_12	0.03	0	0.59	0	0	0.04	1
Precipitation of Wettest Month = bio_13	0.18	0.55	0.59	0.01	0	0.24	2
Precipitation Seasonality (Coefficient of Variation) = bio_15	0.19	0.12	0.52	0.01	0.03	0.09	1
Precipitation of Driest Quarter = bio_17	0.09	0	0.32	0.01	0	0.25	0
Precipitation of Warmest Quarter = bio_18	**0.7**	**0.73**	**0.79**	**0.76**	**0.8**	**0.75**	**6**

Supplementary Table 2. Relative importance (TSS score) of BIOCLIM variables east of the Rift Valley. Major contributing BIOCLIM[1] variables highlighted in grey, for each of the six niche modelling methods.

Description	MAXENT	GLM	GAM	RT	GBM	MARS	No. in top 3
Annual Mean Temperature = bio_1	**0.22**	**0.32**	**0.48**	**0.06**	**0.42**	**0.2**	**6**
Isothermality (BIO2/BIO7) (* 100) = bio_3	0	0.05	0.11	0.05	0	0.04	0
Temperature Seasonality (standard deviation *100) = bio_4	0.01	0.04	0.11	0.02	0.01	0.05	0
Temperature Annual Range (BIO5–BIO6) = bio_7	0.01	0.08	0.12	0.05	0.03	0.03	0
Annual Precipitation = bio_12	**0.77**	**0.99**	**0.81**	**0.57**	**0.6**	**0.89**	**6**
Precipitation of Wettest Month	0.01	0.41	0.36	0.05	0.07	0.32	1
Precipitation Seasonality (Coefficient of Variation) = bio_15	0.07	0.23	0.49	0.06	0.41	0.24	2
Precipitation of Driest Quarter = bio_17	0.18	0.66	0.38	0.09	0.09	0.68	3
Precipitation of Warmest Quarter = bio_18	0.04	0.05	0.2	0.03	0.01	0.05	0

Supplementary Table 3. Relative importance (TSS score) of BIOCLIM variables west of the Rift Valley. Major contributing BIOCLIM[1] variables highlighted in grey, for each of the six niche modelling methods.

BIOCLIM Layer	Description
BIO1	Annual Mean Temperature
BIO3	Isothermality (BIO2/BIO7) (* 100)
BIO4	Temperature Seasonality (standard deviation *100)
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter

Supplementary Table 4. The nine BIOCLIMS used for SDMs. Derived from the full BIOCLIM dataset[1] of 19 variables.

References (also cited in the main paper)

1 Hijmans RJ, Cameron SE, Parra JL, Jones PG & Jarvis A. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* **25**, 1965–1978 (2005).

2 Knutti R & Sedláček J. Robustness and uncertainties in the new CMIP5 climate model projections. . *Nat. Clim. Chang.* **3**, 369–373, doi:doi:10.1038/nclimate1716 (2013).

Paper III. Coffee Farming and Climate Change in Ethiopia. Impacts, Forecasts, Resilience and Opportunities.

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The principal authors of this report are J.M. and A.P.D., with contributions from the other authors. J.M. processed, presented and analysed the data.

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Royal Botanic Gardens Kew

ECFF
Environment & Coffee Forest Forum

Coffee Farming and Climate Change in Ethiopia

Impacts, Forecasts, Resilience and Opportunities

Summary Report 2017



The Strategic Climate Institutions Programme (SCIP)

The SCIP Fund was designed to build Ethiopia's capacity to cope with climate change across the public, private and civil society sectors and to respond to the challenges of transitioning to a Climate Resilient Green Economy (CRGE).

Building a climate-resilient coffee economy for Ethiopia

A two-year SCIP project undertaken by the Royal Botanic Gardens, Kew, and the Environment and Coffee Forest Forum (ECFF), and partners. The aim of the project was to provide a climate-resilient coffee economy strategy for Ethiopia, based on a rigorous assessment of the influence of climate change on coffee-producing areas and wild coffee forests. The climate resilient strategy was developed in close partnership with stakeholders, including government and non-government bodies, coffee producers and industry. A summary of the strategy is presented here as the report *Coffee Farming and Climate Change in Ethiopia – Impacts, Forecasts, Resilience and Opportunities.*

Front and back cover picture: Sorting coffee by hand

Leaves of Arabica coffee

Coffee Farming and Climate Change in Ethiopia: **Key messages**

1

The coffee growing landscape of Ethiopia is varied and complex

Coffee farming in Ethiopia takes place over a vast area, under a wide variety of production systems and various growing conditions, with many different cultivation practices.

2

The climate of Africa and Ethiopia has changed and will continue to change throughout this century

The climate of Africa and Ethiopia has changed. Ethiopia has experienced an increase in temperature of around 0.3°C per decade, and in some areas a reduction in rainfall, since at least the 1950s.

3

Coffee growing in Ethiopia has been negatively influenced by climate change and deforestation

Feedback from coffee farming communities, and observations on coffee production and coffee plant stress, indicate that climate change has already had a negative impact. In some coffee areas, there has been dramatic forest loss.

4

Climate change will continue to impact and alter coffee growing in Ethiopia over the coming decades

Many areas that are suitable for coffee growing in the present day will become less suitable in the future, and in some cases unsuitable. Conversely, substantial areas that were previously unsuitable for coffee farming will become suitable.

5

Relocation of coffee farms/areas will be a key component in building resilience for the Ethiopian coffee economy

Many higher altitude areas will become more suitable for coffee production throughout this century. Migration to these areas will be vital for ensuring resilience in the Ethiopian coffee sector.

6

Appropriate adaptation measures could ensure resilience for many coffee farmers

On-farm adaptation and improvements in coffee farming practices could ensure resilience for many farmers.



Fruits of Arabica coffee, ripening



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Coffee Farming and Climate Change in Ethiopia

Introduction



1

The coffee growing landscape of Ethiopia is varied and complex

2

Africa and Ethiopia's climate has changed and will continue to change

Sorting coffee by hand

1

The coffee growing landscape of Ethiopia is varied and complex

Coffee growing in Ethiopia

In its wild state, Arabica coffee (*Coffea arabica*) is a forest plant restricted to the highlands of Ethiopia and a small area in neighbouring South Sudan[1]. It has been used in Ethiopia as a food and beverage for many hundreds, if not thousands, of years. Thus, Ethiopia can be considered as the biological and cultural home of coffee. Its early use was no doubt restricted to gathering fruits from the wild forests, with semi-domestication possibly coming soon afterwards. Today, an estimated 525,000 hectares (5,250 km^2) of coffee are planted in Ethiopia[2], although the actual area is probably in excess of 20,000 km^2. Coffee provides Ethiopia with its most important agricultural commodity, contributing around one quarter of its total export earnings[3]. In 2014/15 Ethiopia exported around 180,000 metric tonnes of coffee[4] at a value estimated to be in excess of 800 million USD. Ethiopia is Africa's largest coffee producer and the world's fifth largest exporter of Arabica coffee[4], even though yields (kg/hectare) are low compared to other producing countries. Coffee farming alone provides a livelihood income for around 15 million Ethiopians (16% of the population), based on four million smallholder farms[2, 3, 5]. For many of these farmers, coffee is their single most important source of income.

Ethiopia is the main storehouse of genetic diversity for Arabica coffee, and this has several key implications. For the coffee sector and consumers, the most notable of these is the broad diversity of flavour profiles exhibited by Ethiopian coffees. These profiles are associated with geographical location (which is often referred to as 'origin', in a similar way as 'terroir' is used in the wine industry) and factors associated with harvesting and processing. Included among these origins are the well-known coffees of Sidamo, Yirgacheffe, Harar, Nekemte and Limu, but there are numerous lesser-known coffee regions that have equally distinct flavour profiles. The range of flavour profiles adds a unique element to Ethiopian coffee, and makes it especially well-suited to development within the speciality coffee market. As we will see below, Ethiopian coffee production offers protection for biodiversity and other environmental benefits.

Coffee consumption in Ethiopia

Ethiopia is unique among the world's coffee producing countries in that around 50% of the coffee it produces stays within the domestic market, for consumption by Ethiopians. Drinking is not just part of everyday life, it is also deeply embedded in Ethiopian culture. Apart from the well-known Ethiopian coffee ceremony, coffee is used at major events such as marriage and birth, regionally-specific celebrations, and as a medium to build and sustain relationships between family, friends and community.

Coffee farming systems

Ethiopian coffee is mainly grown under the shade of trees (shade or forest coffee), either within forest or forest-like environments, or in farming systems that incorporate specific shade plants – usually indigenous (native) trees, or sometimes fruit trees and other crop plants. In some areas coffee is grown with little or no shade (sun coffee). Forest (shade) coffee and sun coffee can be considered as the two main coffee production systems in Ethiopia. Irrigation is confined to few locations, and mostly where water is easily available and can be diverted to the farm using simple means (e.g. diversion from rivers using trenches). Irrigation is mainly practiced in Amhara and Benishangul-Gumuz Regions, and the north east part of Oromia Region in the Harar coffee zone (See Figure 1, Table 1). The use of chemical inputs, such as pesticides, fungicides and artificial fertilisers is rarely practiced, and although certification is not common[5], Ethiopian coffee can often be considered as organic by default, and may indeed exceed the standards set for organic certification.

Coffee farming alone provides a livelihood income for around 15 million Ethiopians (16% of the population), based on four million smallholder farms.

Forest (shade) coffee can be divided into two broad categories: forest coffee and semi-forest coffee. The forest coffee system uses wild stands of coffee, which exist naturally within the forest, and the farmer undertakes minimal management and intervention. Semi-forest coffee is more intensive, with increased farming interventions (e.g. thinning of trees, understory clearance and weed cutting, and planting of coffee seedlings).

Sun coffee farming systems are usually small and mostly fall into the category of coffee gardens, which are planted in a regular-sized plot at high density. Sun coffee is usually found at higher altitudes (1700–2100 m), often near dwellings, and is characteristic of coffee farming in the Harar coffee zone.

Coffee gardens are often planted close to dwellings and range from a few plants up to a plot of around 100 plants. Coffee gardens are usually part of a mixed cropping system and provide coffee for the household, local consumption or the wider market. Coffee gardens are planted in either shade or sun.

Agroforestry systems are typically family run, of between a quarter and one hectare, and comprise a wide variety of crops in association with indigenous (native) forest cover. The coffee is usually grown under the shade of indigenous trees with other crops on the margins, or in more open places. In the Sidamo area (including Yirgacheffe), coffee is almost exclusively produced within an intensively-managed agroforestry system.

Coffee farms/plots are dedicated to coffee growing for profit, and are typically around one to two hectares, sometimes less (a quarter hectare) or more (five hectares). The area is mostly dedicated to coffee growing, with few other crops, or may be intercropped, as in agroforestry systems. Most coffee farms use shade, provided by tree cover, but some are situated in partial to full sun.

Coffee plantations are large and intensively-managed systems, mostly planted within forest (shade). There is no definitive size limit for a plantation but generally they are more than ten hectares. Large commercial plantations (e.g. over 500 hectares) are uncommon and contribute less than 5% of exportable production.

Coffee producing regions and areas

Within Ethiopia, coffee is produced within specific agro-ecological zones over numerous political divisions. Most coffee is grown in areas of humid (moist) evergreen forest. This type of rainforest is found at 650–2600 m above sea level[6], with coffee mainly confined to altitudes of 1200–2100 m. These forests are cool-tropical, distinctly seasonal (Figure 2), and mostly comprise evergreen trees and shrubs, with a high diversity of other plants and associated fauna. In some highland areas, mostly at the higher range for Arabica coffee (1900–2100 m), coffee farming is undertaken in a drier type of vegetation, dominated by evergreen trees or shrubs, and common native coniferous species[6], particularly in the Harar coffee zone.

The main coffee growing areas (Figure 1) are found within Oromia Region and Southern Nations, Nationalities, and Peoples' Region (SNNPR), with modest production in Amhara Region and minor output in Benishangul-Gumuz Region. In this document, we have divided the coffee lands into five coffee zones, and 16 coffee areas (Table 1, Figure 1).

The majority of coffee production is from the largely forested main coffee zone of the South West, followed by the Sidamo (including Yirgacheffe) coffee area in the South East coffee zone. Harar was once a major producing area but has declined considerably since the 1960s, and possibly decades before. The other coffee zones (Rift and North; Table 1, Figure 1) are modest to minor producers compared to the South West and Sidamo.



Drying washed coffee (parchment)

Position in Ethiopia	Main coffee zone	Coffee area	Region (administrative)
West of Rift Valley	North	*Amhara*	Amhara
		Benishangul-Gumuz	Benishangul-Gumuz
	South West	*Wellega*	Oromia
		Illubabor	Oromia
		Jimma-Limu	Oromia
		Tepi	SNNPR and Gambela*
		Kaffa	SNNPR
		Bench-Maji	SNNPR
Rift Valley	Rift	*Rift North*	SNNPR and Oromia*
		Rift South	SNNPR
East of Rift Valley	South East	*Sidamo (including Yirgacheffe)*	SNNPR and Oromia*
		Bale	Oromia
		Central Eastern Highlands	Oromia
	Harar	*Arsi*	Oromia
		West Hararge	Oromia
		East Hararge	Oromia

Table 1. Main coffee zones and areas and their position within Ethiopia. See Figure 1.
Notes: * Minor part of region only. SNNPR = Southern Nations, Nationalities, and Peoples' Region.

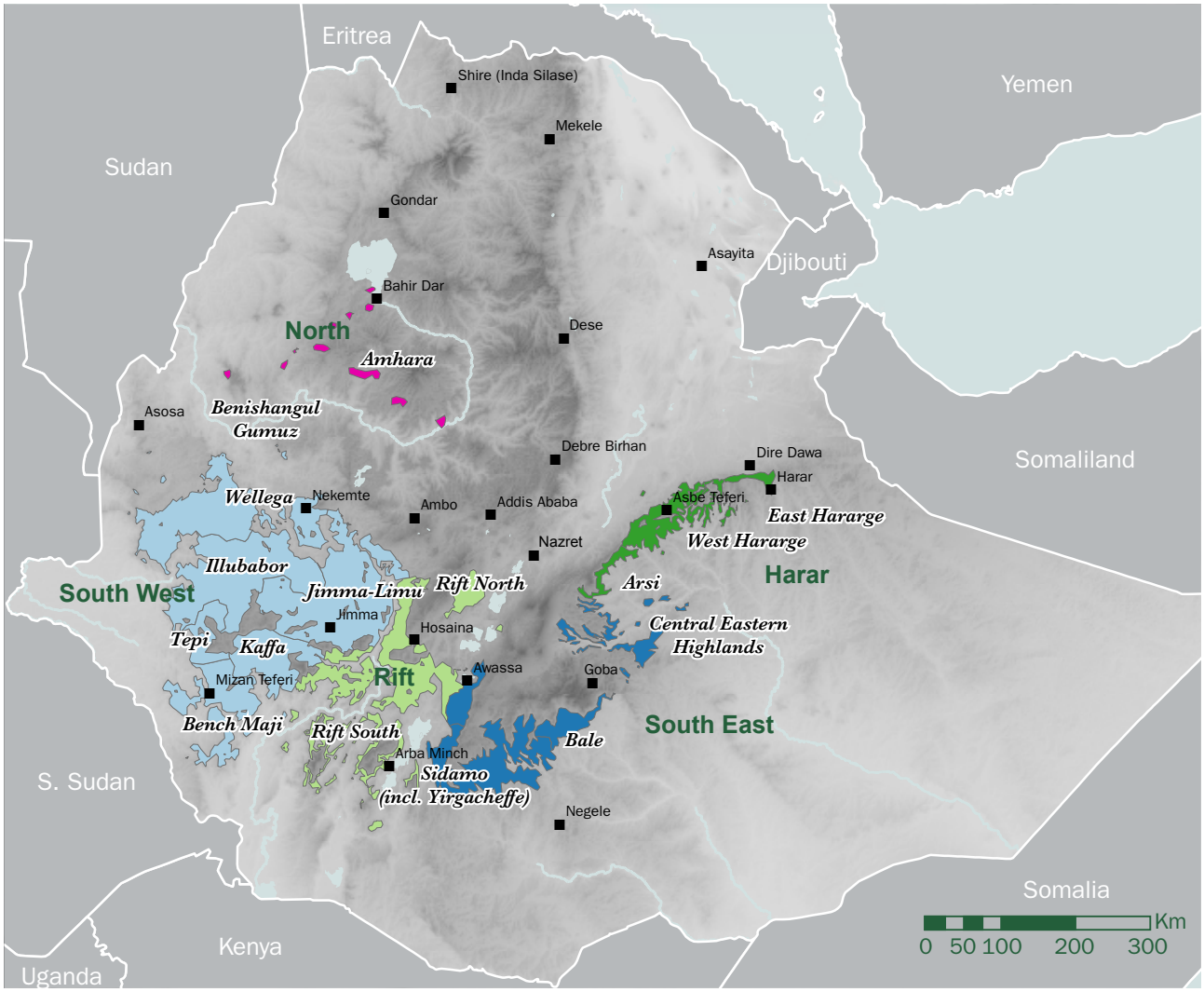


Figure 1. The main coffee growing areas of Ethiopia. See Table 1.

Ethiopia is Africa's largest coffee producer and the world's fifth largest exporter of Arabica coffee.
In 2015/16 total production was 6.4 million 60 kg bags, of which 3.7 million were consumed within Ethiopia[4].

Overview of Ethiopia's coffee growing climate

Arabica coffee grows successfully – producing a marketable crop – within a narrow range of environmental conditions. The interplay between rainfall, temperature and seasonality are the main factors governing coffee plant growth. Coffee will become increasingly stressed as the air temperature increases and soil moisture decreases (due to lack of rainfall), and vice versa. Yearly differences in temperature and rainfall are largely due to seasonality, i.e. annual weather patterns.

The Seasons

The climate of Ethiopia's coffee lands is tropical, but due to the large central highland area (mostly above 1000 m) much of the country can be classified as cool-tropical. The seasons are largely defined by rainfall. There are three main seasons: Bega, Belg, and Kiremt (or Kremt).

Bega (October to January/February) — the long dry season. This is when coffee harvesting and processing takes place. The severity of the main dry season depends largely on location but also on other physical characteristics, including altitude, slope and aspect. There may be slight to moderate rainfall or barely any at all.

Belg (February to May) — the first rains before the main wet season, which may either represent the early part of the wet season, or a distinct short wet season followed by a short dry period before the main rains. This is the main period for coffee flowering, fruit initiation and early development.

Kiremt/Kremt (June to September) — the main wet season. Where the Belg period is distinct from the main wet season, the rainfall pattern is referred to as bimodal (east of the Rift Valley); where the yearly rainfall is confined to Kiremt, the rainfall pattern is unimodal (west of the Rift Valley). This is the period for final coffee fruit development and ripening. Around the end of September there is a sharp decline in rainfall, Kiremt comes to an end, and the dry season begins.

Throughout the coffee lands, temperatures are generally higher during the dry season and lower in the wet season(s). Seasonal rainfall and temperature profiles for six coffee growing locations are shown in Figure 2.

Rainfall (precipitation)

Rainfall is the most important factor governing the distribution of coffee farming and wild coffee forests in Ethiopia[8] (Figures 1, 2). The distribution of rainfall varies greatly across Ethiopia, according to season, altitude and physical features of the landscape. Clear annual patterns are evident, although rainfall is extremely variable.



Small coffee plantation in forest

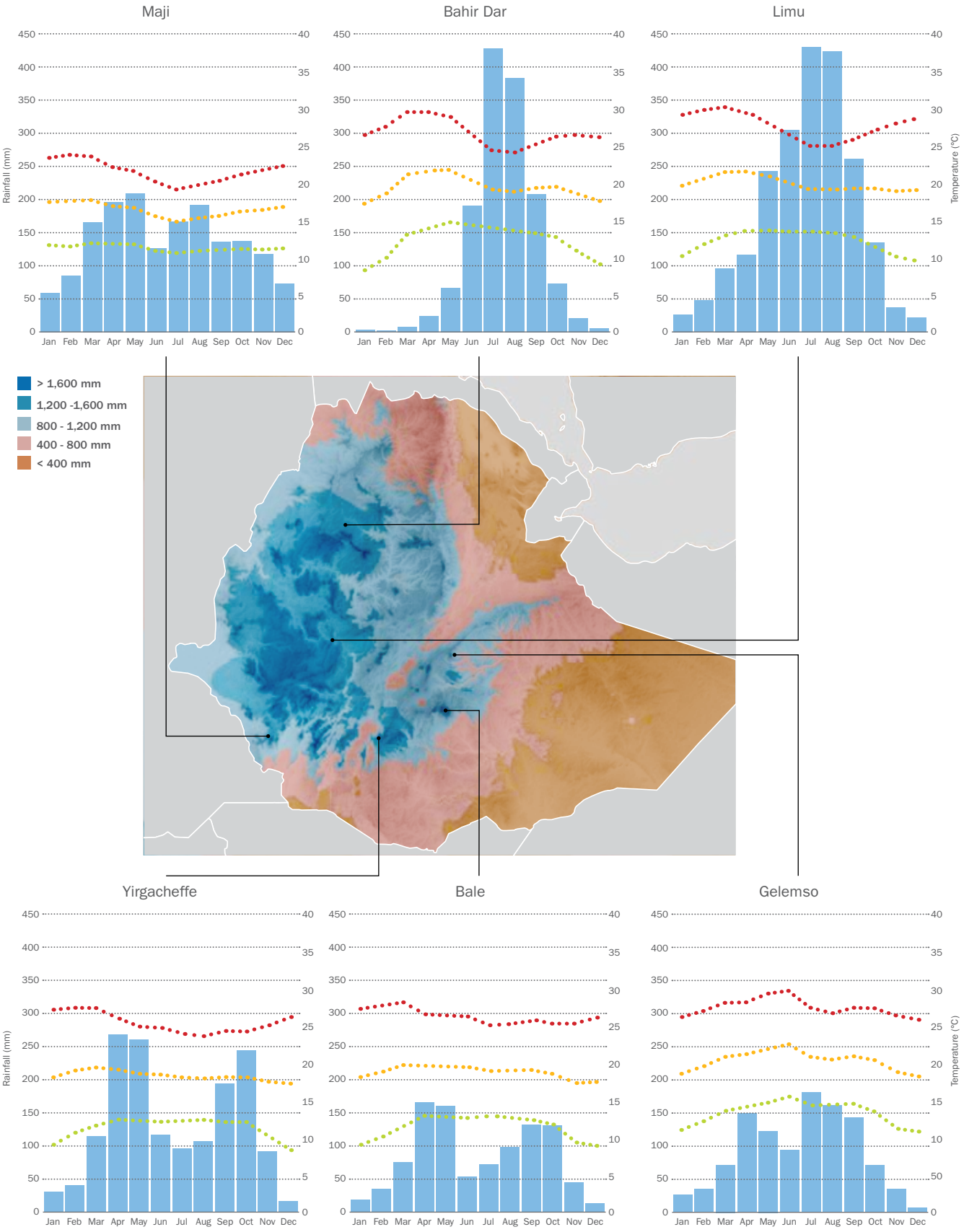


Figure 2. Rainfall map of Ethiopia (background), and rainfall and temperature profiles for six coffee growing locations. Bi-modal rainfall pattern (east of Rift Valley); uni-modal rainfall (west of Rift Valley). Graphs based on historical climate data (30 year averages) and WorldClim[7]. Background yearly rainfall map of Ethiopia from WorldClim[7]. See Endnotes.

The highest rainfall is on the western side of the Rift Valley, in the main South West coffee zone. The coffee areas of the South West typically receive 1500–2100 mm of rain per year. In the southern part of South West coffee zone there is generally less annual rainfall (1300–1700 mm per year). The North coffee zone, including Amhara and Benishangul-Gumuz coffee areas, receives 1400–1800 mm per year, although the rains come later in the year and end earlier, compared to the South West. This results in a shorter, more intense wet season and a longer dry season (Figure 2, and Endnotes).

On the eastern side of the Rift Valley, the Harar coffee zone usually receives far less total rainfall than all other coffee areas (800–1200 mm per year). The Sidamo coffee area in the south is wetter (1200–1600 mm per year), and the Bale coffee area somewhere in-between (1000–1400 mm per year).

Air temperature

The ideal average minimum temperature for Arabica coffee is 12–14˚C, which in most cases occurs between sunset and sunrise; it will survive temperatures at or just below 0˚C for short periods (hours). The ideal average temperature is 18–22˚C, with an ideal average maximum (daytime) temperature of 25–27˚C. Maximum temperatures of 30–32˚C are not lethal if they exist for short periods (hours), and if there is sufficient water available in the soil. Extreme temperatures for coffee beyond 32˚C up to 34˚C, and perhaps even a high as 38˚C, can be tolerated by Arabica plants for very short periods (a few hours), but only if there is adequate water in the soil. If the soil is not wet enough, then extreme maximum temperatures for plant survival will be lower; for example, temperatures around 30˚C could be lethal within less than 24 hours if the soil is too dry.

Temperatures vary according to locality, altitude, season and physical features of the landscape. In the coffee areas on the western side of the Rift Valley, the minimum temperature is typically 11–14˚C, the average 15–21˚C, and maximum 23–27˚C. In the coffee areas on the eastern side of the Rift Valley, the minimum is 9–13˚C, the average 16–20˚C, and maximum 24–26˚C. Altitude has a direct and almost uniform relationship on air temperature, with an approximate decrease of 0.6˚C for every 100 m increase in altitude. However, other physical factors (e.g. slope and aspect), weather (especially wind), and vegetation (e.g. forest cover) will also have an influence, depending on location and time of year.

Humidity and other factors

In the coffee areas of Ethiopia, humidity is mainly linked to rainfall and temperature. In the dry season (October to January/February) the monthly average relative humidity (RH%) of a typical coffee growing area of the South West zone is usually 55–80 RH%, and the wet season (June to September) 90 RH% or higher. There is a considerable difference in humidity between day (low RH%) and night (high RH%). The amount of sun (sunshine hours) is linked to seasonality, with greater cloud cover and less sunshine in the wet season(s), and less cloud and more sun in the dry season.



Arabica coffee plant

2

Africa and Ethiopia's climate has changed and will continue to change

The Intergovernmental Panel on Climate Change (IPCC), the leading international body for the assessment of climate change, states that warming of the climate system via human activity is unequivocal due to increases in the concentrations of greenhouse gases in the atmosphere. Their *Fifth Assessment Report*[9] states that the atmosphere and oceans have warmed, the amounts of snow and ice have diminished, the sea level has risen, and the concentrations of greenhouse gases have increased. In the following section we have summarised the findings of the IPCC reports, and other sources, relevant to Africa and Ethiopia.

Observed changes

Temperature

Africa

Decadal analyses of temperatures strongly point to an increased warming trend across the African continent over the last 50–100 years[10, 11]. Surface (near surface) temperatures have increased by 0.5°C or more during the last 50–100 years over most parts of Africa, with minimum temperatures warming more rapidly than maximum temperatures[10]. Over the last 50 years there has been an increase in seasonal mean temperature in many areas of Ethiopia, Kenya, South Sudan, and Uganda[10, 12, 13, 14].

Ethiopia

Historical data from weather stations for Ethiopia provides specific details of the general warming trend. Data shows that the mean annual temperature has increased by 1.3˚C between 1960 and 2006, at an average rate of 0.28˚C per decade[15], and by 0.3°C per decade in the south western region[16]. Our own data analyses of climate stations support these findings (Figure 3). Observations also show significantly increasing trends in the frequency of hot days, and much larger increasing trends in the frequency of hot nights; the frequency of cold days has decreased significantly in all seasons except the dry season (December, January and February)[15, 17].



Sun-drying coffee

Data shows that the mean annual temperature has increased by 1.3˚C between 1960 and 2006, at an average rate of 0.28˚C per decade[15], and by 0.3°C per decade in the south western region[16].



Coffee making ceremony

Rainfall (precipitation)

Africa

Most areas of the African continent lack sufficient climate station data to draw conclusions about trends in annual rainfall over the past century. In many regions there are also discrepancies between different rainfall data sets, and precipitation patterns over the continent are extremely complex[10]. Precipitation in eastern Africa shows a high degree of variability with respect to location and timing (seasonality) and is highly influenced by the physical characteristics of the land surface (e.g. the position and height of mountains)[10]. Despite these constraints and difficulties, it has been reported that over the last three decades rainfall has decreased by around 15% over eastern Africa, in the main growing season (March and May/June)[12, 13, 14, 18]. The suggested link to the decrease in rainfall is rapid warming of the Indian Ocean, which causes an increase in convection and precipitation over the tropical Indian Ocean, contributing to the decrease in rainfall over the continental land surface. Other studies also show a decline in the March-to-May seasonal rainfall over eastern Africa[10].

Ethiopia

It has been stated[15] that the strong variability within Ethiopia's annual and decadal rainfall makes it difficult to detect long term trends, and that there is no statistically significant trend in observed mean rainfall in any season for which climate data is available (1960–2006). However, based on data from quality-controlled climate station observations, it has been shown that spring (Belg) and summer (Kiremt) rains have declined by 15–20% since the mid-1970s and late 2000s, in southern, south-western and south-eastern Ethiopia[18, 19], particularly in the period of the early rains (Belg – February to May) in the south east and east of the country. An overall reduction of rainfall of around 10% across Ethiopia (1948–2006) has also been reported[16]. See also Figure 3.

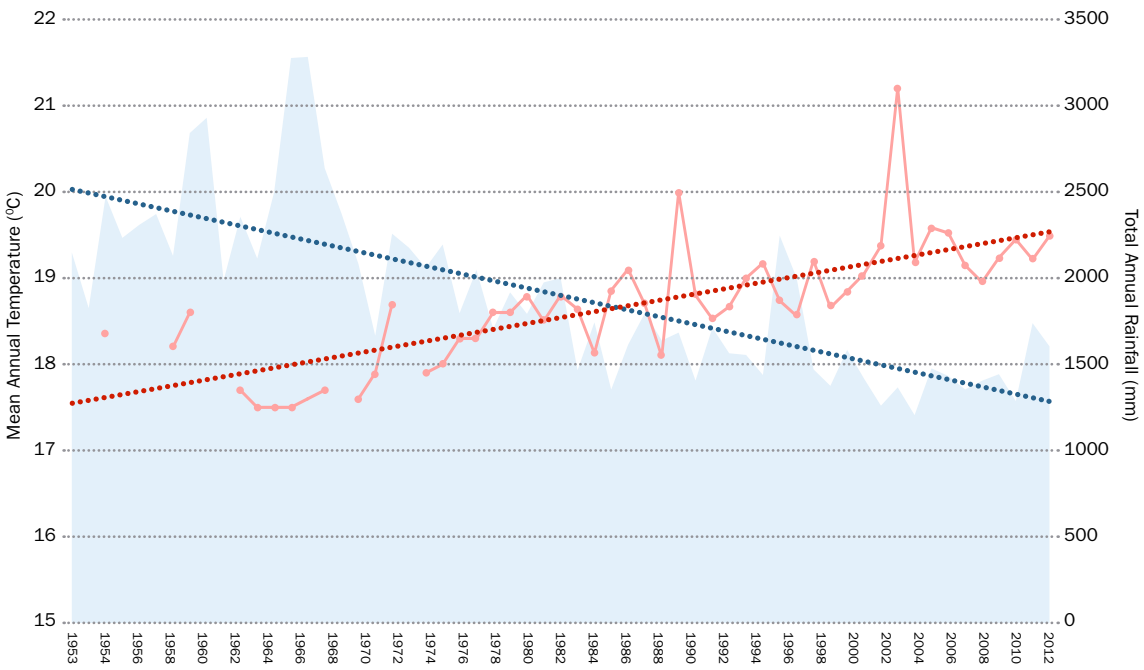


Figure 3. Historical climate data from Gore (South West Ethiopia), showing an increase in average (mean) air temperature, and decrease in total annual rainfall, since 1953. Solid red line and red dots show recorded annual mean temperatures (gaps in the line represent missing temperature records); blue shading/peaks show recorded total annual rainfall. Dashed red line represents the temperature trend (increasing); dashed blue line represents the annual rainfall trend (decreasing).

Predicted future change

Temperature

Africa

The Representative Concentration Pathways (RCP) are the latest generation of modelled scenarios that provide input to climate models. Warming projections under a low emissions RCP (RCP 2.6) indicate that Africa will see a change of around 1°C (and less than 2°C) by the end of this century, relative to the late 20th century mean annual temperature baseline[10, 11]. Under a high emissions RCP (RCP 8.5) an increase of more than 2°C could occur by the mid-century across much of Africa and exceed 4°C by the end of the century[10] (Figure 4). It is likely that land temperatures over Africa will rise faster than the global land average, particularly in the more arid regions, and that the rate of increase in minimum temperatures will exceed that of maximum temperatures[10].

Ethiopia

The mean annual temperature of Ethiopia is projected to increase by 1.1–3.1˚C by the 2060s, and 1.5–5.1˚C by the 2090s, with the scale of the projections depending on the emission scenario[15]. Climate model projections under the A2 and B1 scenarios show warming in all four seasons across the country, which could cause a higher frequency of heat waves as well as higher rates of evapotranspiration[21].

Rainfall (precipitation)

Africa

Projected rainfall change over Africa in the mid and late century is uncertain. There is low confidence in projected increases of heavy precipitation over most of Africa, except East Africa, where there is a high confidence in a projected increase in heavy precipitation[22]. However, regional climate model studies also suggest drying over most parts of Uganda, Kenya, and South Sudan in August and September by the end of the 21st century[23].

Ethiopia

Projections from different General Circulation Models (GCMs) are broadly consistent in indicating increases in annual rainfall in Ethiopia[9, 10], but these increases are largely due to increasing rainfall in the October–December period in southern Ethiopia[15]. Projections of change in the rainy seasons of April–June and July–September, which affect larger areas of Ethiopia, are much more uncertain but tend towards slight increases in the south west and deceases in the north east[15]. In the Ethiopian Highlands, a region of high and complex topography, projections from the GCMs also indicate likely increases in rainfall, and extreme rainfall, by the end of the 21st century[10]. However, these future trends are not consistent with observed decreasing rainfall for many places in Ethiopia (from the 1950s to the present day). Overall, projections based on GCMs for Ethiopia are highly variable[21] and for some regions the various GCMs do not agree on the direction of precipitation trend.

Under a high emissions RCP (RCP 8.5) an increase of more than 2°C could occur by the mid-century across much of Africa and exceed 4°C by the end of the century[10].

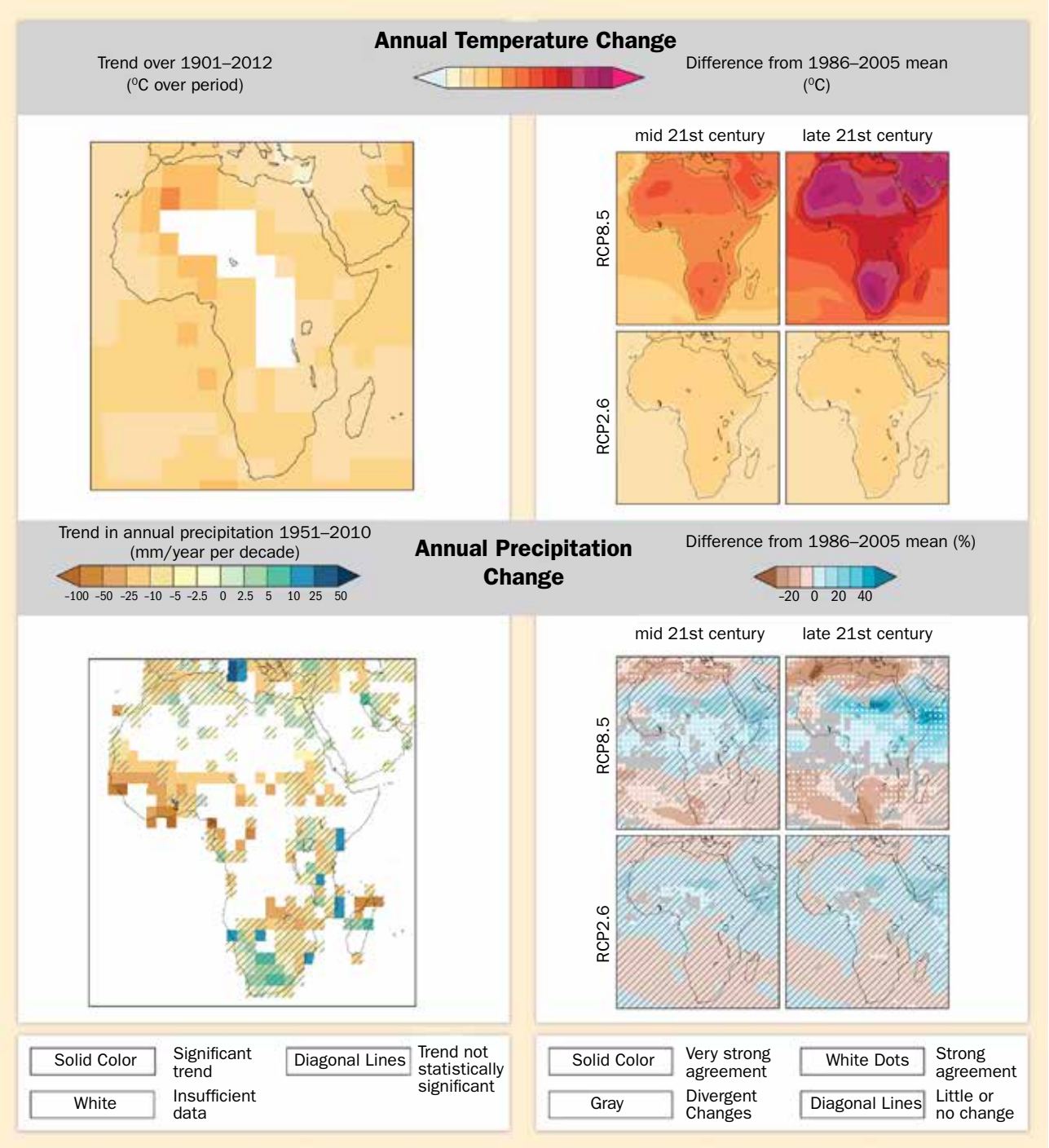
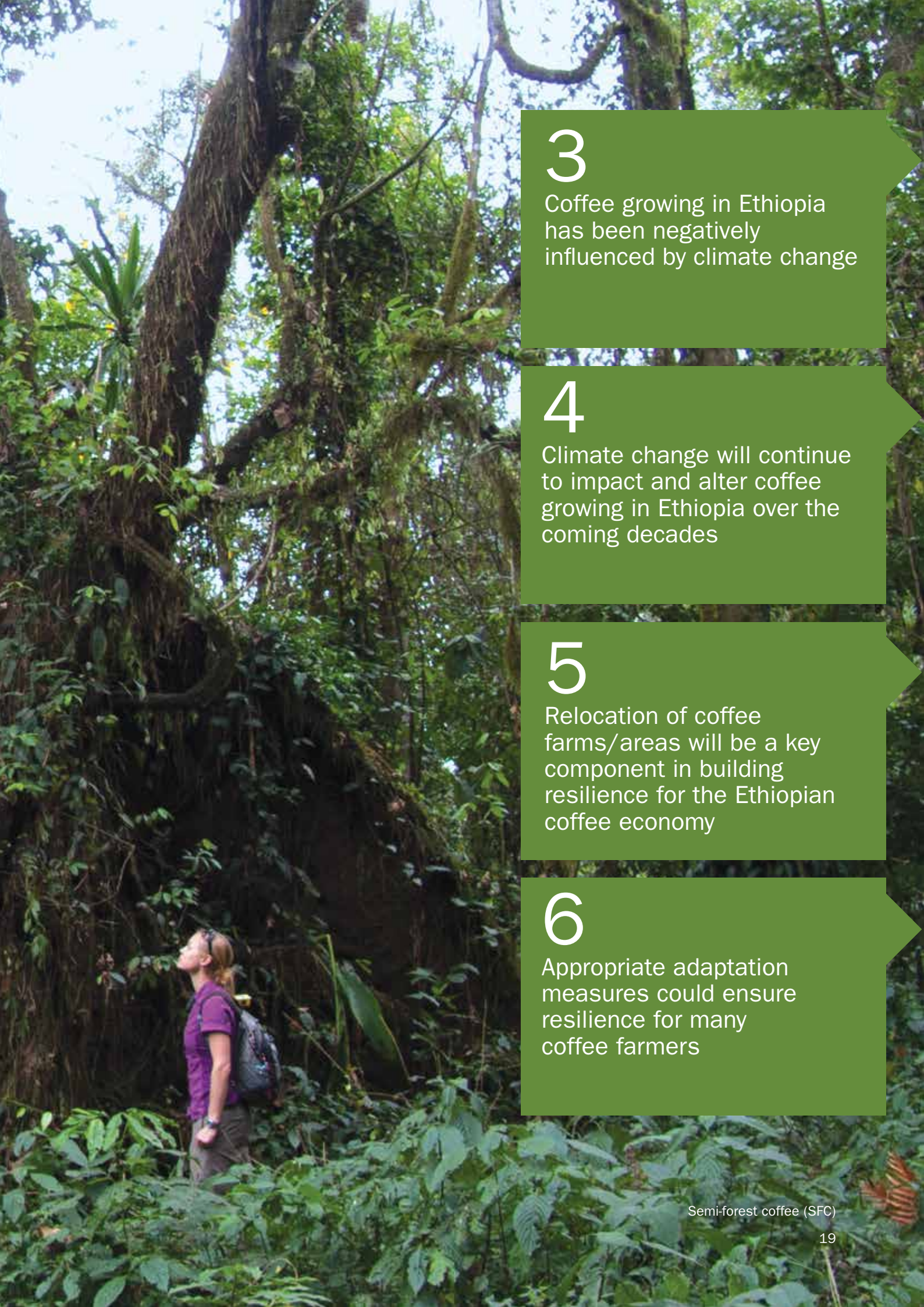


Figure 4. Observed and projected changes in annual average temperature and precipitation for Africa. From IPCC report: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects: Africa, Figure 22–1[10]. See Endnotes for full legend. Notes. Representative Concentration Pathways (RCPs) for Africa: under RCP 2.6 temperatures would increase by around 1˚C (but less than 2˚C) by 2081–2100; under RCP 8.5 temperatures would increase by around 4˚C (up to 5.8 ˚C) by 2081–2100[10].



Building a Climate Resilient Coffee Economy for Ethiopia

SCIP project findings, analyses and main recommendations



3

Coffee growing in Ethiopia has been negatively influenced by climate change

4

Climate change will continue to impact and alter coffee growing in Ethiopia over the coming decades

5

Relocation of coffee farms/areas will be a key component in building resilience for the Ethiopian coffee economy

6

Appropriate adaptation measures could ensure resilience for many coffee farmers

Semi-forest coffee (SFC)

3

Coffee growing in Ethiopia has been negatively influenced by climate change

Present-day suitability for coffee growing in Ethiopia

The importance of understanding present-day suitability

Present-day environmental suitability for coffee growing has been used here as the base-line for climate-related coffee growing observations and projections. Some of Ethiopia's coffee growing areas are already poorly suited for growing coffee, and it is mainly these areas that have been impacted by climate change and will continue to be so in the future. In Figure 5, we present a simplified present-day suitability map for forest coffee. Comparison between the main coffee areas shows very clearly which areas have the highest suitability for coffee farming and which do not. This does not mean, however, that all the areas identified as unsuitable (i.e. uncoloured) will not be able to grow good quality coffee. Local conditions can make a large difference, due to the microclimate, and groundwater levels, while some areas receive greater farming inputs (e.g. irrigation, improved shade).

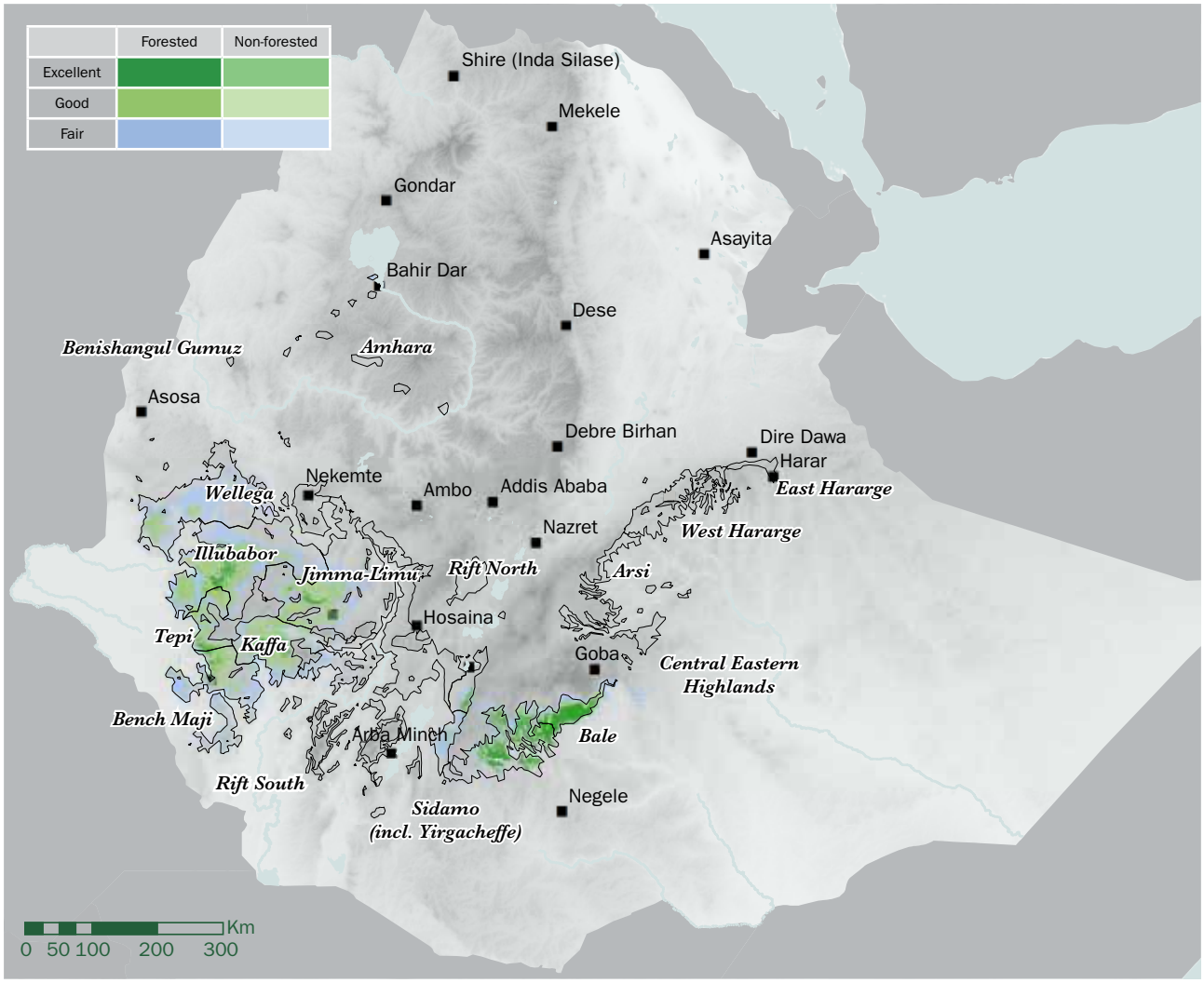


Figure 5. Present-day suitability for forest coffee production in Ethiopia, with modelled coffee suitability (the niche) and remaining forest. Map based on environmental data[7], high resolution satellite imagery[24], and field observations (see Endnotes, and legend for Figure 7 for definitions of fair, good and excellent).

The importance of forest

Forest cover is important for coffee because it provides the right conditions for successful cultivation, by reducing daytime air and soil temperatures, increasing humidity and preserving soil moisture. It also has key benefits for agricultural (and natural) ecosystems, including nutrient recycling, soil preservation, watershed preservation, pollination services, temperature buffering, shelter from wind and heavy rainfall, and carbon storage. Ethiopia coffee forests also provide a home for a diverse assemblage of plants and animals, and are thus important for biodiversity preservation.

Feedback from coffee farmers and direct observation

Feedback from coffee farmers

During extensive field survey (2013–2016) we interviewed farmers and farming communities about perceived changes in coffee farming, on a year-by-year and generation-by-generation basis, across Ethiopia. The main theme of the feedback was that weather patterns are now more variable than in the past, and that the climate has changed. The most common comments were: an increase in the uncertainty in the yearly weather pattern, particularly in rainfall variability and the onset of the wet season; an extension of the dry season (and thus shortening of the wet season); a more extreme (drier and hotter) end to the main dry season; more extreme weather (heavier rain, hotter days, and warmer nights); and a very gradual, long-term decrease in rainfall, including some indication of a notable shift to less rain in the late 1970s and mid-1980s. Many of these observations have been reported elsewhere for Ethiopia[25] and East Africa[26]. This feedback was not evenly distributed over the coffee landscape, and some farmers reported little or no change in the climate, or few major weather-related issues. In general, areas identified as environmentally problematic for coffee farming (Figures 2, 5) received the most negative climate-related feedback, in terms of the number of comments and their severity.



Green coffee after hulling

Specific regional comments are also significant. See Figure 1 for coffee areas. On the Zege / Zeghie Peninsula (Amhara coffee area), it was said that the dry season is longer compared to several decades ago; from the 1930s there has been a shift from yearly to two-yearly harvests, and then to a good harvest roughly every five years (since the 1980s). In the Wellega coffee area, between Nekemte and Dembi Dolo, farmers and coffee sector representatives report a general decline in coffee production, with a decreasing frequency of good harvests, from once a year to every second or third year, and a general increase in drought during the end of the dry season. Coffee farms in the western part of the Wellega coffee area (1700–2000 m) report general diminishing rainfall as a problem, but with fewer lost harvests than other parts of Wellega. The coffee areas of Illubabor, Jimma-Limu, and Kaffa report increases in the unpredictability of the seasons (especially rainfall), an increase in the severity of the dry season, and an increase in the number of warmer days and nights, with locations at and below 1500 m most severely affected. In the Bench Maji coffee area, farmers also report drought issues, due to an extension of the dry season and a general increase in warm days. In the Sidamo coffee area (including Yirgacheffe), there is a perception of a more severe end to the main dry season, both before and after the early rains, with generally less rainfall and higher daytime temperatures. In the Harar coffee zone, farmers report an increase in the frequency and severity of droughts, and a gradual reduction in rainfall over several decades.

Observations of climate-related stress on coffee plants

The best time to observe and assess stress in coffee plants is towards, or at the end of, the dry season in February and March, although observations throughout the year are also worthwhile and sometimes unexpected. Our stress assessments for the SCIP project were restricted to major, easily discernible indicators: the wilting of leaves (mild to severe), wilting and curling of leaves; leaf fall (few to many); and death of the plant (total loss of all leaves, wood dead). Coffee crop production was recorded, as were major pests and diseases and their severity. On-the-spot measurements were taken for ambient air temperature, soil temperature and soil moisture (at various depths).

During the project we observed many cases of mild to severe plant stress, and also plant death, towards the end of the dry season (February to early April). The most severe stress conditions (wilting and curling of leaves, loss of coffee crop, and plant death through drought) were recorded in the Harar coffee zone, particularly in Arsi (Figure 1). In many Harar coffee gardens, cultivation appeared to be lacking suitable farming practices (e.g. mulching, terracing or irrigation) required for growing coffee in this area which, due to low rainfall, is not ideally suited to coffee production. In 2015, we recorded the death of a large number of coffee plants in Arsi at 1400–1600 m; many hundreds of hectares of once profitable coffee plantation had died due to severe drought. Other areas showing marked stress of coffee plants were the Zege / Zeghie Peninsula in the Amhara coffee area, the Wellega coffee area, between Nekemte and Dembi Dolo, and coffee farms in the main South West coffee zone below 1400 m. In all cases stress was caused by low soil moisture, in combination with high temperatures (25°C +).

During the project we observed many cases of mild to severe plant stress, and also plant death, towards the end of the dry season (February to early April).

Other impacts of climate stress on coffee plants

Environmental stresses can influence coffee growing in a number of ways, from slight physiological stress (discernible using scientific apparatus), to the obvious physical manifestations of water and/or heat stress, from wilted leaves (mild stress) to the death of the plant (severe stress), as discussed above. Coffee plants may also show climate-related stress through the increased occurrence, and increased intensity (and diversity), of diseases and pest attacks. When growing conditions are not suitable, coffee crop production is also likely to decline or fail. During prolonged drought episodes, for example, there is often a reduction in coffee bean size, and an increase in bean malformations, which are often referred to as ‘faults’. Faults, such as black marks, blackened beans, misshapen beans and insect damage, are measured by industry standards and have a direct influence on coffee prices, in combination with cup quality. Cup quality, how good or bad the coffee smells and tastes, is assessed by rigorous, standard protocols, in conjunction with the number of faults. These quality scores place coffee into a category, which traders use to set the grade for the coffee and hence its price. Even quite small changes in the coffee growing climate, within each year’s growing season (e.g. low rainfall), can influence yield and cup quality. We observed a close link between coffee quality and the environment: areas identified by our coffee suitability (niche) modelling as unsuitable or marginal generally produced lower quality coffee (Figures 5 and 7a). This was evident on the Zege / Zeghie Peninsula (the northern part of the Amhara coffee area), Harar, eastern Wellega, Bench Maji, and the Rift (see Figures 1 and 5).

We observed a close link between coffee quality and the environment: areas identified by our coffee suitability (niche) modelling as unsuitable or marginal generally produced lower quality coffee.



Wild coffee forest, Kaffa (SW Ethiopia)

4

Climate change will continue to impact and alter coffee growing in Ethiopia over the coming decades

Climate change modelling for coffee production in Ethiopia, 1960 to 2099

Coffee suitability (niche) modelling, forest cover from satellite data[24], and ground control points (the location of coffee production sites) were used to compute land-surface coffee production maps for Ethiopia (see Endnotes). These maps were tested and refined via exhaustive ground survey during visits to coffee farms, coffee forests, and non-coffee areas across Ethiopia. Once satisfied that the maps accurately represented the coffee growing landscape of Ethiopia, we rigorously applied computer modelling to project what would happen in the future under various climate change simulations using numerous General Circulation Models (GCMs), and then made assessments as to how much variability there was in the forecasts. Overviews of the modelling outcomes, for four time intervals (1960–1990, 2010–2039, 2040–2069, 2070–2099), are summarised below for the main coffee areas in tabular form (Table 2) and in Figures 6 and 7.

By the end of this century our projections show that the current coffee growing areas of Ethiopia will decrease considerably, if no interventions are made (Figures 6, 7; Table 2). At the other extreme, with active migration and intervention, there could be a substantial increase in the coffee farming area of Ethiopia (see Section 5).



Pre-sorting of coffee fruits prior to pulping and washing



Washed coffee for sale

Caveats

Climate change modelling and the use of GCMs for predicting the implications and impact of future climate change is fraught with difficulties and challenges, not least the uncertainty of future events. In this study we have done our upmost to present a balanced and unbiased view, and attempted to present uncertainty and disagreement where it exists in the modelling. The modelling has been rigorously back-referenced to field observations and historical data in order to reconcile modelled future outcomes with observed or assumed climate change trends.

At the other extreme, with active migration and intervention, there could be a substantial increase in the coffee farming area of Ethiopia [see Section 5].

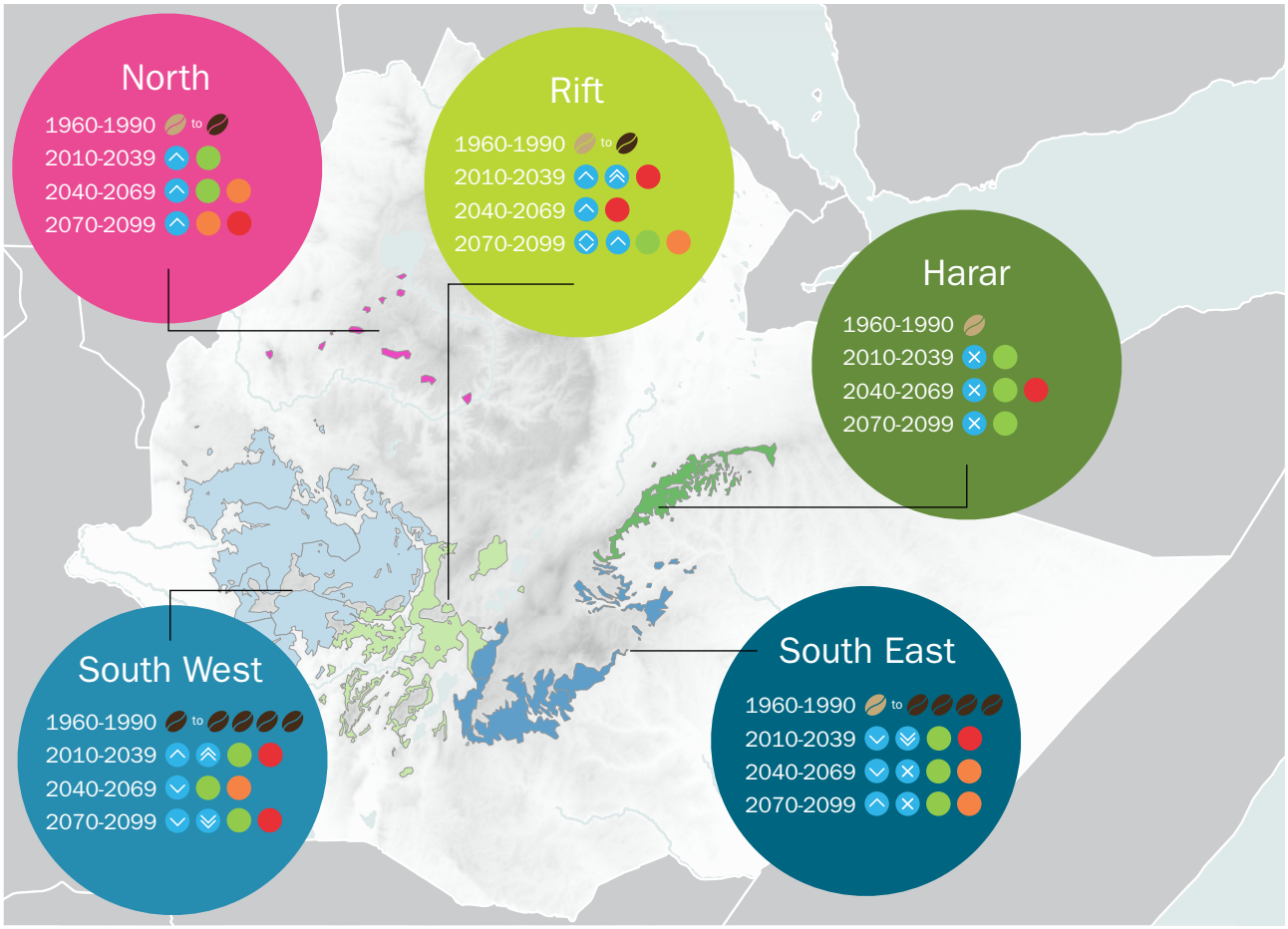


Figure 6. Summary of major change for the main coffee zones of Ethiopia by the end of this century. See Table 2 and Figure 7 for further details.

Unsuitable
Marginal
Fair
Good
Excellent

Coffee suitability
Considerable improvement
Improvement
little or no change
Decline
Considerable decline
Mixed outcome
Lost (no longer exists)

Model agreement
Strong
Moderate
Weak

Examples. North coffee zone: in the recent-past (1960–1990) coffee suitability is classified as unsuitable to marginal, with an overall improvement in coffee suitability through to 2099, although model agreement is mixed (projections are uncertain). Harar coffee zone: in the recent-past (1960–1990) coffee suitability is classified (broadly) as unsuitable, with no improvement (actually dropping below unsuitable) through to 2099; model agreement is strong (projections have high agreement).

Position in Ethiopia	Main coffee zone	Coffee Area	1960 – 1990	2010 – 2039	2040 – 2069	2070 – 2099	Notes
West of Rift	North	*Amhara*	Unsuitable – marginal	Marginal	Marginal – Fair	Fair	A small coffee area, with potential emergence of new coffee areas in the future
		Benishangul-Gumuz	Unsuitable – marginal	Marginal	Marginal – Fair	Fair	A small coffee area, with potential extension in the future
	South West	*Wellega*	Marginal – good	Marginal – good	Marginal – Fair	Marginal	A general decline apart from improvements on higher ground in south-west part of the area
		Illubabor	Fair – excellent	Good – excellent	Good – excellent	Fair – excellent	Shift of coffee suitability to higher ground; declining long-term at lower elevations; south-east corner of area stable (retains excellent suitability)
		Jimma-Limu	Fair – excellent	Good – excellent	Good – excellent	Fair – good	Shift of coffee suitability to higher ground; declining long-term
		Tepi	Fair – excellent	Good – excellent	Good – excellent	Fair – good	Shift of coffee suitability to higher ground; declining long-term
		Kaffa	Fair – excellent	Good – excellent	Good – excellent	Fair – good	Shift of coffee suitability to higher ground but declining long-term
		Bench-Maji	Fair – excellent	Fair – excellent	Fair – good	Fair – excellent	A general decline in suitability, with shift to excellent suitability to higher ground in south of area
Rift Valley	Rift	*Rift (north)*	Unsuitable	Unsuitable – marginal	Unsuitable	Unsuitable	Steady decline in coffee suitability in the medium- to long-term
		Rift (south)	Unsuitable – marginal	Marginal – good	Marginal – good	Unsuitable – Good	A mixed outlook, with an improvement in coffee suitability in some parts of the area, espcially in south
East of Rift	South East	*Sidamo (including Yirgacheffe)*	Fair – excellent	Marginal – good	Marginal – good	Marginal – Excellent	Very variable, with improvements due to shift in suitability to higher ground
		Bale	Good – excellent	Unsuitable – marginal	Unsuitable	Unsuitable	A decline in suitability in the near-future, and not regaining suitability afterwards
		Central Eastern Highlands	Marginal – good	Unsuitable	Unsuitable	Unsuitable	Overall the area is marginal in the present day; rapidly becoming unsuitable
	Harar	*Arsi*	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Overall the area is unsuitable in the present day, and remaining so
		West Hararge	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Overall the area is unsuitable in the present day, and remaining so
		East Hararge	Unsuitable	Unsuitable	Unsuitable	Unsuitable	Overall the area is unsuitable in the present day, and remaining so

Table 2. Summary of projected climate change impact on coffee suitability for major coffee areas, based on computer modelling. Examples: coffee suitability in the Amhara coffee area is likely to be improve throughout this century, although General Circulation Model (GCM) agreement towards the end of the century (2070–2099) is weak; coffee suitability in the Illubabor coffee area is projected to increase in the medium-term (2010–2069), but with a decline at the end of the century (2070–2099), with strong agreement across GCMs for all time periods; coffee suitability in the Bench Maji coffee area is projected to decline in the medium-term (2010–2069) but in the long-term (2070–2099) the outlook is mixed, GCM agreement is weak across all time periods. See Figure 7 for more detail.

Coffee Suitablity change (peroid on peroid)
Considerable improvement
Improvement
Little or no change
Decline
Considerable decline
Mixed outcome
Lost (no longer exists)

Model agreement
Strong
Moderate
Weak

Present-day suitability for coffee

Coffee gardens: coffee growing ranges from a few trees to small plots. Yields may be poor and inconsistent, or good, largely depending on inputs (e.g. irrigation) and / or local conditions (microclimate, water table).

Unsuitable: coffee production is either barely possible or impossible (empty hexagons; see also Figure 7b).

Marginal: coffee production is possible but often problematic, with poor and very inconsistent yields.

Fair: coffee growing is possible and sometimes good, but may require additional inputs (e.g. irrigation, shade or better shade, and pruning). Yields poor in years with low rainfall.

Good: coffee production is good, with the potential for consistent, high quality yields. Yield and quality may be negatively influenced in some years (during adverse weather conditions, especially low rainfall and high temperatures).

Excellent: coffee production is good to excellent, with the potential for consistent, high quality yields. Yields and quality can be negatively influenced by adverse weather conditions, but this is less likely.

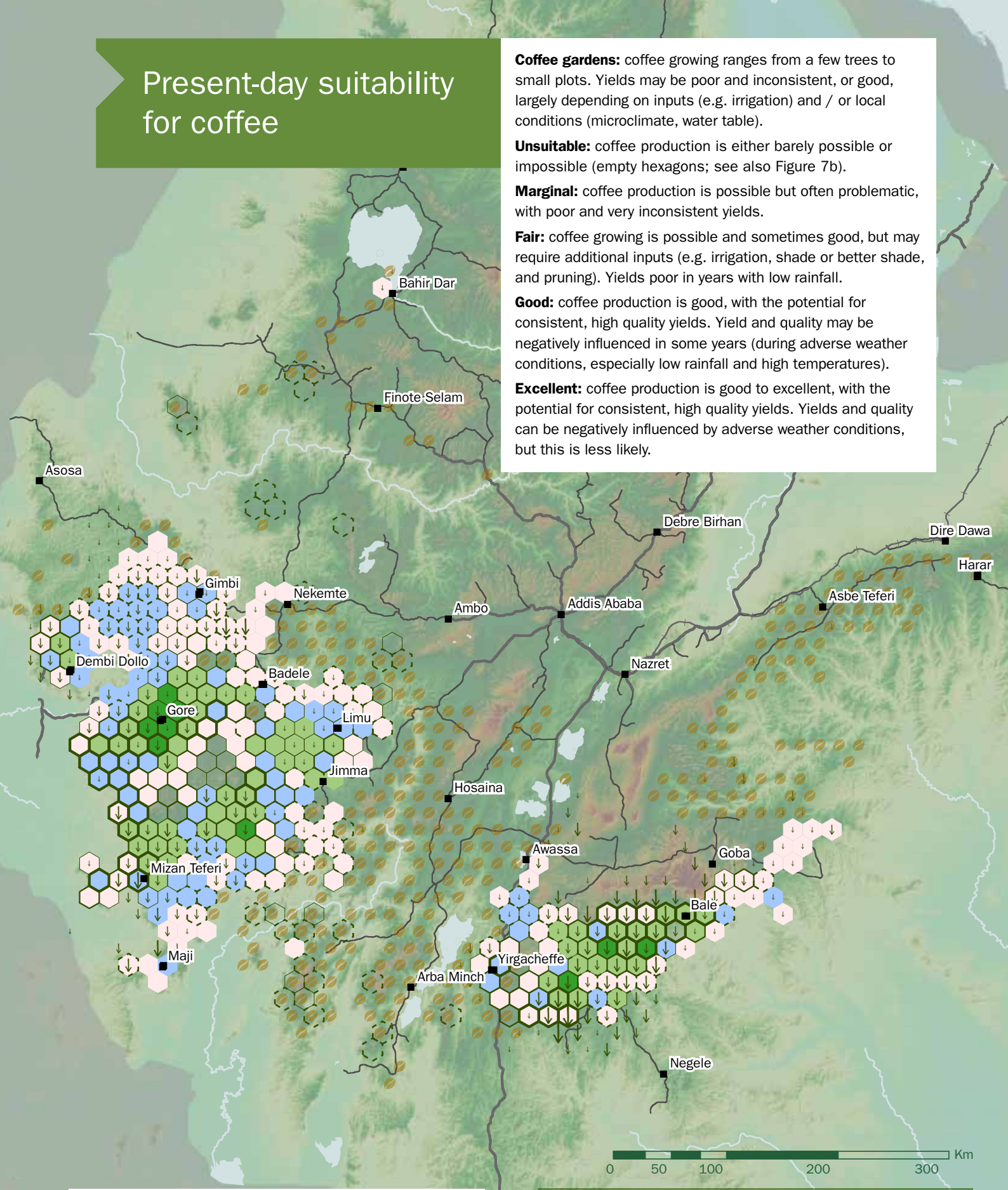


Figure 7a. Present-day suitability for coffee.
Forest change: relative amount of deforestation, c. 2000–2013. Forest cover: relative amount of forest expressed as a percentage (100% = intact forest cover). Coffee suitability (niche): – potential suitability for coffee growing or wild coffee forests based on environmental parameters (rainfall, temperature, seasonality).

Suitability for coffee at the end of this century

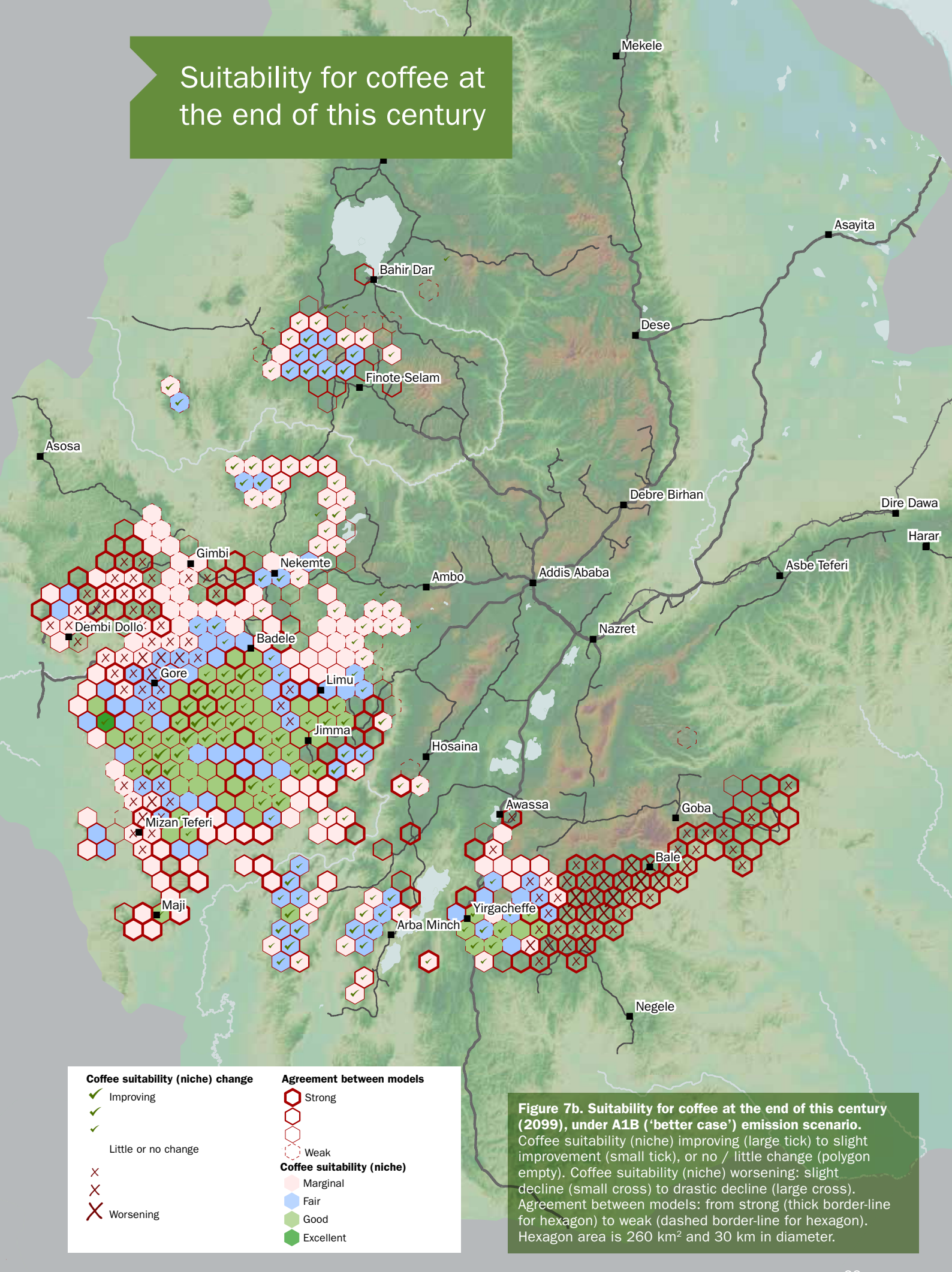


Figure 7b. Suitability for coffee at the end of this century (2099), under A1B ('better case') emission scenario. Coffee suitability (niche) improving (large tick) to slight improvement (small tick), or no / little change (polygon empty). Coffee suitability (niche) worsening: slight decline (small cross) to drastic decline (large cross). Agreement between models: from strong (thick border-line for hexagon) to weak (dashed border-line for hexagon). Hexagon area is 260 km^2 and 30 km in diameter.

5

Relocation of coffee farms/areas will be a key component in building resilience for the Ethiopian coffee economy

Climate change will negatively impact much of the current coffee farming landscape of Ethiopia, however, substantial areas that were previously unsuitable for coffee will become suitable as the century progresses. This is due to the upslope shift of coffee growing suitability (the niche) as higher altitude areas (e.g. above 2000 m) improve and lower altitude areas worsen, as the climate changes.

Assisted migration to 'new' areas will be a key component for ensuring resilience in the Ethiopian coffee economy due to the replacement of areas lost at lower altitudes (below 1400–1500 m) as the climate there becomes unsuitable for coffee growing. The new areas are mostly in the South West coffee zone, but North, Rift (Rift South coffee area), and South East (Sidamo coffee area) coffee zones may also provide opportunities (Table 2, Figures 6 and 7).

Relocation of coffee farms to higher altitudes will require positive action with critical attention to feasibility and planning. Before decisions are made concerning the establishment of new coffee farms and areas, suitability has to be determined in terms of climate, agronomy (e.g. soil, shade, slope), the potential for land-use contradictions (e.g. land tenure, other existing land-use activities), market value, and logistics. A certain amount of shift could occur quite naturally, as farmers see the potential and financial incentive to start growing coffee on their land in areas previously unsuitable (e.g. because it was too cold).

In many cases afforestation and reforestation will be necessary to provide the right growing environment for coffee, but this would also bring additional benefits in terms of increasing forest cover, preserving biodiversity and providing improvements in ecosystem services. Prevention of forest loss is also a key issue, especially in the South West and South East coffee zones where recent deforestation rates are high (Figure 7a) and could have a more significant impact than climate change, at least in the short to medium term.

As part of the adaptation process it will be essential to undertake dedicated, on-the-ground monitoring to track the course of climate change and assess its impact on coffee production and farming communities.

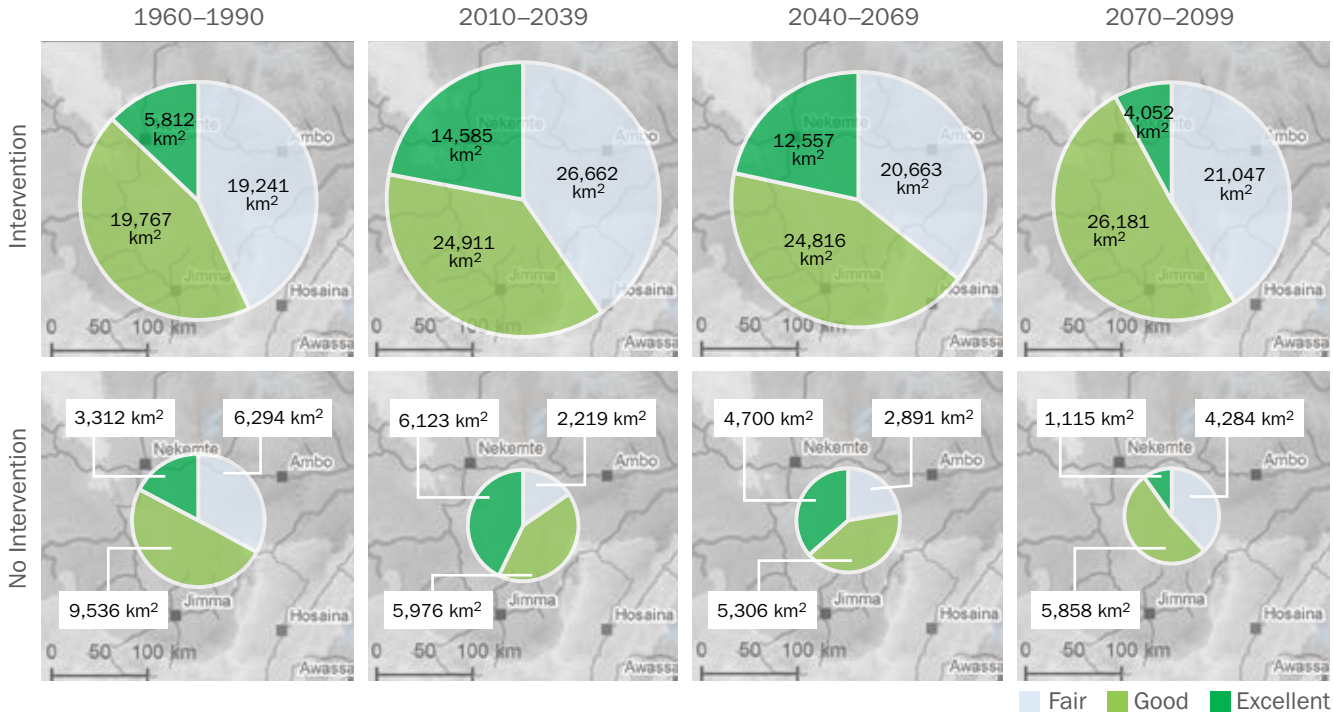


Figure 8. Coffee suitability (niche) area (km²), 1960–2099. **Intervention.** Suitability potential (allowing for assisted migration of coffee farms/areas and increased forest cover). **No Intervention**. Suitability based on present day forest cover (no assisted migration, no increase or decreases in forest cover). Background (part of southeastern Ethiopia) is given to provide scale only.

6

Appropriate adaptation measures could ensure resilience for many coffee farmers

Air and soil temperature and moisture can be altered by specific farming interventions, and provide a buffer against inadequate growing conditions and extreme weather events. The most obvious interventions are irrigation, shade management and mulching, but terracing has clear benefits, and pruning is also advocated in some cases. Observations of on-farm adaptation and improvements in coffee farming practices across Ethiopia indicate the potential to provide various levels of resilience for many (but not all) farmers. Careful assessment of each farming site is required to see which interventions, or combination of measures, would be most suitable. Table 2, and Figures 5, 6 and 7 provide a general guide as to the scale, timing and longevity of interventions, although a case-by-case approach is required to assess the potential for specific locations.

Improved cultivars and selections of indigenous Arabica coffee may provide some potential, especially for disease resilience and improved productivity[27], but significant climate resilience is unlikely based on field observations of field trials, and available genetic diversity information.

Key adaptation measures

Irrigation: The use of extra water to boost and/or maintain soil water availability for coffee plants is an ancient and highly effective means of improving yield and quality. If irrigation practices are good, Arabica coffee can be successfully grown in places that would otherwise be unsuitable due to low rainfall. There are numerous examples in Ethiopia where good to excellent coffee is grown with low-cost irrigation systems.

Tree shade management: Effective shade management can improve coffee growing conditions by reducing daytime air and soil temperatures, and increasing humidity and soil moisture. The difference in daytime temperatures between shaded and unshaded coffee plots can be around 4°C. Choice of shade tree species, planting density and canopy coverage are key factors in good shade management. Effective shade management can also counter the negative effects of heavy rain (e.g. run-off prevention, and coffee flower protection from heavy raindrops) and drying winds.

Mulching: Covering the soil with different materials (e.g. compost, manure) not only helps to preserve soil moisture and decrease soil temperature (reducing evapotranspiration), but it can also increase soil fertility, supress weeds, and improve rainfall penetration into the ground. Mulching has been used to good effect in Kenya, Tanzania and other countries in East Africa.

Terracing: This is practiced in Harar and Rift coffee zones. Terracing has numerous benefits, including drastic improvements in soil quality (e.g. an increase in depth, moisture, and fertility), and reductions in water run-off and soil erosion. Terracing requires expertise and, sometimes, considerable resources, although low-intensity terracing systems are possible in some areas. Terracing can be particularly effective when used in combination with irrigation.

Pruning: This can improve coffee harvests by maximising cropping potential and re-invigorating old, unproductive trees. Improvements in yield can offset losses encountered during previous harvests. Pruning may also help to improve water-use efficiency in coffee plants.

Main recommendations

1 Timely, precise, science-based decision making is required now, and over the coming decades, to ensure sustainability and resilience for the Ethiopian coffee sector.

2 A climate monitoring program (including a dedicated network of weather stations) should be established and maintained to track the course of climate change, and assess its impact on coffee production and farming communities. Areas of rapid and significant change, both observed and forecast (e.g. the Bale coffee area), should be prioritised.

3 As climate and climate change science improves, it will be necessary to re-evaluate and update future forecasts for coffee production.

4 A concerted effort should be made to identify and establish new coffee areas at higher altitudes. Particular attention should be placed on competing land-use issues (e.g. existing land use, land tenure, nature conservation sites), soil and climate suitability, road access and other infrastructure, and adequate return-on-investment. A sustainability strategy for Ethiopian coffee production lacking relocation of coffee farms / areas is likely to be ineffective, especially if countrywide production levels are to be maintained or increased.

5 Forest preservation and re-establishment, and good management of soils and watersheds, will play a significant role in adaptation and should be an integral part of future planning. Prevention of forest loss is a key issue, especially in the South West and South East coffee zones where recent deforestation rates are high, and could have a more significant impact than climate change at least in the short to medium term.

6 Increases in coffee productivity (kg/hectare) and quality should be accelerated via improvements in agronomy and processing, respectively.

7 Recent improvements in the coffee value chain need to be accelerated across Ethiopia, including coffee sector governance and logistics.

8 Resources should be allocated to helping farmers diversify away from coffee in places where climate change has made coffee farming economically unviable.

9 Prices paid to farmers for their coffee needs to be increased and stabilized. This will provide better opportunities for resilience due to an increase in the potential for on-farm investment and income-loss offsetting (including harvest insurance schemes).

10 For many farms, there needs to be greater investment in locally appropriate, cost-effective adaptation measures to improve resilience, including mulching, irrigation, improved shade management, terracing, and pruning.

11 Further research is required in order to ascertain the precise outcomes and benefits of on-farm interventions, particularly terracing, mulching, irrigation, pruning, and shade management. Attention should also be paid to new and emerging technologies.

12 A coffee governing body should be formed, with the remit of ensuring advocacy and effective governance for coffee sustainability and resilience.

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All of the reports and most of the scientific publications are available online.

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Green coffee in warehouse, awaiting transportation

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ENDNOTES

Extra notes for Figures.

Figure 2. Bahir Dar (Zege/Zeghie Peninsula). Sufficient annual rainfall, but the dry season (October to February/ March) is too dry and coincides with highest temperatures. The bulk of the rain falls in the main wet season (May/ June to September). Coffee suitability is marginal (coffee growing possible but often problematic, with poor and very inconsistent yields) and is often negatively influenced by drought during the dry season. **Limu**. Sufficient rain throughout the dry season (October to February) and good rains in the main wet season (May/June to September). Highest temperatures coincide with sufficient rainfall. Coffee suitability is excellent (coffee production good to excellent, with the potential for consistent, high quality yields). **Maji**. Sufficient rain throughout the dry season (October to February) and good rains in the main wet season (May/June to September). Highest temperatures coincide with sufficient rainfall. Coffee suitability is excellent (coffee production good to excellent, with the potential for consistent, high quality yields). Slight bimodality to main season rainfall pattern. **Gelemso**. Barely sufficient rain throughout the dry season (October to February) and low rainfall in the main wet season(s) (April to September). Highest temperatures may not always coincide with sufficient rainfall. Coffee suitability is unsuitable to marginal (coffee growing possible but often problematic, with poor and inconsistent yields) especially without intervention (e.g. irrigation). **Bale**. Barely sufficient rain throughout the dry season (October to February), and low rainfall in the main wet season(s) (April to September); low rainfall is offset by slightly lower temperatures. Coffee suitability is good to excellent (coffee production good to excellent, with the potential for consistent, high quality yields). Yield and quality may be negatively affected in some years (during adverse weather conditions, especially low rainfall). **Yirgacheffe**. Sufficient rain throughout the dry season (November to February) and sufficient rainfall in the main (and slightly extended) wet season(s) (April to October). Highest temperatures usually coincide with sufficient rainfall. Coffee suitability is good to excellent, with the potential for consistent, high quality yields. Yield and quality may be negatively affected in some years (during adverse weather conditions, especially low rainfall). For further interpretation, see Tables 1 and 2, Figures 1, 5, 6 and 7.

Figure 4. From IPCC report: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects: Africa, Figure 22-1[10]. Observed and projected changes in annual average temperature and precipitation for Africa. Observed and projected changes in annual average temperature and precipitation for Africa. **Top panel, left.** Map of observed annual average temperature change from 1901–2012, derived from a linear trend [WGI AR5 [8] Figures SPM.1 and 2.21]. **Bottom panel, left.** Map of observed annual precipitation change from 1951–2010, derived from a linear trend. [WGI AR5[9] Figures SPM.2 and 2.29] For observed temperature and precipitation, trends have been calculated where sufficient data permit a robust estimate (i.e. only for grid boxes with greater than 70% complete records, and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colours indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. **Top and bottom panel, right.** CMIP5 multi-model mean projections of annual average temperature changes and average per cent changes in annual mean precipitation for 2046–2065 and 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colours indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-year means) and ≥90% of models agree on sign of change. Colours with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Grey indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on assign of change. Colours with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant changes at shorter timescales such as seasons, months, or days. Analysis uses model data and methods building from WG1 AR5[9] Figure SPM 8, and Boxes 21–2 and CC–RCI[9].

Images by: Jenny Williams (front and back cover, and pages 2, 4, 8, 12–14, 21, 23, 24 and 37); and Aaron Davis (pages 10, 18, 25 and 34).

Overview of methods

Ground survey, field observations and ground control points

For the SCIP project (2013–2016), ten field expeditions were made across the coffee landscape of Ethiopia, covering at least 30,000 km. We used historical distribution data (800 records) from as far back as 1941, and made more than 800 records during the course of the project, giving a total of over 1,600 ground control points.

Forest Mapping

The maps for coffee forest extent were produced from Landsat 8 imagery[24] from 2013/14, using 38 images for 24 scenes (to allow the removal of cloud cover). Forest change data extracted from Global Forest Watch (http://www.globalforestwatch.org/)[28].

Modelling

Over 2,000 simulations were run to produce the final models, with six modelling techniques used to give a consensus, across four dates (1960–1990, 2010–2039, 2040–2069, 2070–2099. Two emission scenarios were used: A1B and A2 (see below). Twenty-four Global Circulation Models (GCMs) (http://www.ccafs-climate.org/) were reviewed for the project; three were selected as the most robust for Ethiopia (1) BCCR-BCM2-0 = Bjerknes Centre for Climate Research (BCCR), University of Bergen, Norway. Model name, Bergen Climate Model (BCM) Version 2. (2) CSIRO-MK3-5 = Centre for Australian Weather and Climate Research. Model name, Mark 3.5. (3) GFDL-CM2-1 Geophysical Fluid Dynamics laboratory (GFDL) model name Coupled Climate Model 2.1. Models were applied independently to the two main regions (West Rift and East Rift) and six potential migration scenarios were examined using the BioMod 2 package (https://cran.r-project.org/web/packages/biomod2/index.html).

Climate change emissions scenarios

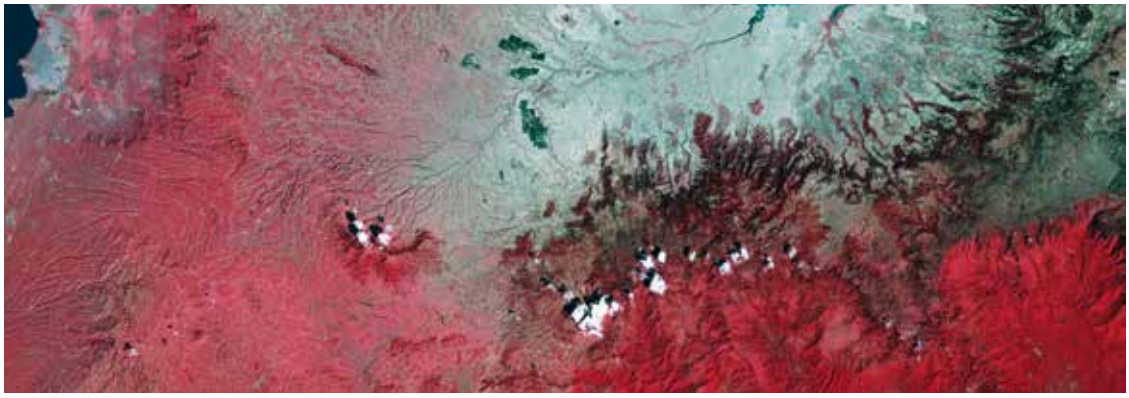
For our future forecasts we used A1B and A2 carbon emission scenarios. As of 2015 we reached 9.8 GtC (billion tonnes of carbon), 60% above 1990 emissions. Under the A1B and A2 scenarios we would reach 13.5 GtC by 2100. Under the A2 scenario we would reach 29.1 GtC by 2100. The A2 scenario tracks a world where we more or less continue as we are; A1B represents a more balanced future energy use (fossil fuels and new technologies). Under A1B global temperatures would increase by 2.8˚C (min. 1.7 to max. 4.4˚C) by 2090–2099; under A2 global temperatures would increase by 3.4˚C (min. 2.0 to max. 5.4˚C) by 2090–2099. It is worth noting that we observe little difference to the coffee models and projections when using these two scenarios.

Further information on project outcomes

Supporting resources for climate resilience in the Ethiopian coffee sector are available online.

Supporting research article
Moat, J., Williams, J., Baena, S., Wilkinson, T., Gole, T.W., Challa, Z.K., Demissew, S. & Davis. A.P. (2017). Resilience potential of the Ethiopian coffee sector under climate change. *Nature Plants* 3: 17081 (2017). DOI: 10.1038/nplants.2017.81 http://dx.doi.org/10.1038/nplants.2017.81

Coffee Atlas of Ethiopia
Davis, A.P., Wilkinson, T., Challa, Z.K., Williams, J., Baena, S., Gole, T.W. & Moat, J. (2017). *Coffee Atlas of Ethiopia*. Royal Botanic Gardens, Kew (UK).



False colour composite Landsat 8 image of the Bale and Rift areas, SE Ethiopia. Darker red represents denser vegetation.



Authors

The principal authors of this report are Aaron Davis and Justin Moat (Royal Botanic Gardens, Kew), with contributions from Tadesse Woldemariam Gole and Zeleke Kebebew Challa (Environment and Coffee Forest Forum – ECFF), Sebsebe Demissew (Addis Ababa University – AAU), and Susana Baena, Jenny Williams and Tim Wilkinson (Royal Botanic Gardens, Kew). Figure 3 is attributed to Mark Lee (Royal Botanic Gardens, Kew). The report should be cited as: Moat, J., Williams, J., Baena, S., Wilkinson, T., Demissew, S., Challa, Z.K., Gole, T.W. & Davis. A.P. (2017). *Coffee Farming and Climate Change in Ethiopia: Impacts, Forecasts, Resilience and Opportunities. – Summary.* The Strategic Climate Institutions Programme (SCIP). Royal Botanic Gardens, Kew (UK). Pp. 37.

Main project partners

Ethiopian Biodiversity Institute (EBI)
National Meteorology Agency (NMA)
Ministry of Environment and Forest (MEF)
Ministry of Agriculture (MoA)
Addis Ababa University (AAU)
Oromia Coffee Farmers' Cooperative Union (OCFCU)

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Coffee leaf tea, coffee husks and dried coffee fruits



Financed by the SCIP Fund

UKaid
from the British people

NORWEGIAN MINISTRY
OF FOREIGN AFFAIRS

Ministry of Foreign Affairs of Denmark

Paper V. Refining area of occupancy to address the modifiable areal unit problem in ecology and conservation.

Published: Conservation Biology

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Pages: 25 + 6 (Supplementary material).

Refining area of occupancy to address the modifiable areal unit problem in ecology and conservation.

Abstract

The 'modifiable areal unit problem' is prevalent across many aspects of spatial analysis within ecology and conservation. The problem is particularly manifest when calculating metrics for extinction risk estimation, for example, area of occupancy (AOO). Although embedded into the International Union for the Conservation of Nature (IUCN) Red List criteria, AOO is often not used or is poorly applied. Here we evaluate new and existing methods for calculating AOO from occurrence records and present a method for determining the minimum AOO using a uniform grid. We evaluate the grid cell shape, grid origin and grid rotation with both real-world and simulated data, reviewing the effects on AOO values, and possible impacts for species already assessed on the IUCN Red List.

We show that AOO can vary by up to 80% and a ratio of cells to points of 1:1.21 gives the maximum variation in the number of occupied cells. These findings potentially impact 3% of existing species on the IUCN Red List, as well as species not yet assessed. We show that a new method that combines both grid rotation and moving grid origin gives fast, robust and reproducible results and, in the majority of cases, achieves the minimum AOO. As well as reporting minimum AOO, we outline a confidence interval which should be incorporated into existing tools that support species risk assessment. We also make further recommendations for reporting AOO and other areal measurements within ecology, leading to more robust methods for future species risk assessment.

Introduction

The modifiable areal unit problem (MAUP) in conservation and ecology

Any operation using a set of shapes (e.g. grid cells) to aggregate data yields different results depending on size, shape and positioning of those objects. The 'modifiable areal unit problem' (MAUP; Gehlke & Biehl 1934; Openshaw 1984) is well known in the field of spatial analysis: when artificial reporting units are imposed on continuous geographic phenomena, or on finer-resolution spatial units, part of the resulting spatial pattern or outcome is an artefact of the size (scale MAUP) and shape (zone MAUP) of the reporting units (Heywood et al. 2011). Ecology and conservation deploy such operations commonly, for example in species richness of grid cells or other polygons, environmental data layers created by aggregating or resampling pixel data from remotely sensed imagery, and area of occupancy (AOO) estimated from occurrence records of species. However, the MAUP is rarely acknowledged and in particular, the shape (zone) MAUP has not been fully explored. Failing to address this problem, especially in the context of assessing species and ecosystem extinction risk, has fundamental implications for conservation planning, policy and management.

MAUP and the IUCN Red List(s)

The IUCN Red List of Threatened Species (RLS) (IUCN 2012) is a globally important tool for assessing extinction risk of species. A complementary system has now been developed for ecosystems: the IUCN Red List of Ecosystems (Keith et al. 2013) [RLE]. Both systems employ metrics associated with geographic range that can be affected by the MAUP. The core process of assessing a species' extinction risk is its assignment to one of nine categories based on five criteria: population decline, geographic distribution, small population size, restricted populations and quantitative analysis of extinction risk (IUCN 2012). If thresholds are met for any one of these criteria, it is sufficient to justify a threat category. Criterion B relates to geographic distribution and is the most heavily utilised criterion (~50% of all assessment; Collen *et al.* 2016), reflecting the considerable, and increasing, availability of species occurrence data (e.g. provided by the Global Biodiversity Information Facility).

Either 'extent of occurrence' (EOO) or 'area of occupancy' (AOO), or both, can be used to determine level of threat under Criterion B. For species and ecosystem assessments, AOO must be estimated as less than threshold values (for species: 10, 500 and 2,000 km² and for ecosystems: 200, 2,000 and 50,000 km^2 respectively for Critically Endangered, Endangered and Vulnerable species, see Supporting information; Table S1), in conjunction with known decline, limited number of locations, fragmentation, or fluctuation of range or population size. In addition, declines in estimated AOO or EOO are sufficient for listing under the same three threat categories under Criterion A, and AOO can also be applied to criterion D2. Thus, estimating AOO and EOO are fundamental to the Red Listing process. The use of EOO has recently been discussed (Joppa et al. 2016), but little attention has been given to ensuring consistency in the approaches used for estimating AOO. To ensure ongoing rigour in Red List assessments we address this knowledge gap.

AOO is the geographic range occupied by the species within its EOO (Gaston 1991, 1994; Gaston & Fuller 2009), excluding cases of vagrancy, at a particular scale (IUCN 2012). It is based on known occurrences (usually points), using a repeatable methodology that superimposes a grid, counts the number of cells occupied and, in the case of species RLS assessments, sums their areas RLE assessments use the number of cells). Errors in AOO estimation can occur when sampling intensity is low, or the taxon has low detection probability (IUCN Standards and Petitions Subcommittee 2016). Another major influence on estimating AOO is scale of grid size, where different grid sizes can under- or over-estimate AOO (Willis et al. 2003). Scale in AOO estimation (an example of the scale MAUP) has been explored and documented elsewhere, resulting in various recommendations ranging from up- and down-scaling to applying different scales depending on the threats (Hui 2009; Keil et al. 2013; Marsh 2016; Keith et al. 2017). Choice of cell size influences AOO estimation and IUCN neutralises this problem by recommending a standard cell size (2 × 2 km cells for the RLS (IUCN 2012) and 10 × 10 km cells for the RLE (Keith et al. 2013)). Further flexibility in estimating AOO for the IUCN criteria is allowed with the application of habitat maps, although maps should be rescaled to the IUCN reference scales (IUCN Standards and Petitions Subcommittee 2016).

MAUP shape/zone

An important consideration that has received little attention so far is whether grid- or cell-based estimates of AOO establish the true minimum value for AOO given the data and scale used. In line with the precautionary principle, the IUCN guidelines (IUCN Standards and Petitions Subcommittee 2016 p. 48) state that "If different grid locations (starting points of the grid) result in different AOO estimates, the minimum estimate should be used", but the consequences of this have not been fully explored. Existing tools such as GeoCAT (Bachman et al. 2011), the equivalent package in R 'rCAT' (Moat 2017), R packages 'ConR' (Gilles et al. 2016) and 'red' (Cardoso 2017), and ArcView extension CATS (Moat 2007), use simple AOO algorithms that can return different results depending on the placement of the grid (Supporting information; Figure S1). Consequently, AOO may frequently be over-estimated and lead to inappropriate (optimistic) Red List assessments. This risks diverting conservation resources away from species or ecosystems most needing them. Keith et al (2017) acknowledged the grid origin problem and adopted an algorithm where grid origin is shifted and minimum AOO is reported when the lowest AOO is not bettered after a number of user defined rounds, see also R package 'redlistr' (Lee & Murray 2017). They noted AOO could be 73% larger or 63% smaller than a mean value (Keith et al 2017). Further work is needed to fully address the impact of shifting grid origin as well as other elements of the zone/shape MAUP such as grid cell shape and grid orientation.

With free and easy-to-use tools for performing AOO estimation, combined with availability of spatial species data, AOO may be applied more frequently. Thus it is important to test different ways of estimating AOO, and provide guidance on how best to achieve the minimum AOO estimate. Our aim here is to develop a fast algorithm that varies both grid cell shape, grid orientation and grid origin with descriptive, reproducible results, whilst achieving minimum AOO most of the time, and accords with the rules of the Red List criteria (IUCN Standards and Petitions Subcommittee 2016). Further, we estimate the number of species globally that may be listed under inappropriate threat categories

because of the shortcomings of existing AOO estimation methodologies. This should have the impact of seeing AOO more widely used and rigorously documented in Red List assessments.

Methods

Overview: we built a simulation environment using the software R (R Core Team 2016), to experimentally test different variables such as grid cell shape (hexagons and squares), grid origin and grid orientation. We applied novel algorithms, developed here, to simulated and real-world test data to calculate AOO, identifying the most efficient (processing time) and appropriate method (lowest AOO).

Data

We used five different datasets of occurrence records, two of which were simulated (see supporting information figure S2), and three real-world (Madagascar, Africa, and Caribbean):

- **Square set of random points,** on a simple 0–10 in X and Y co-ordinate system (simulated): small, simple data set for testing multiple iterations and algorithms.
- **Oval set of random points**, with area of 100 units, orientated at 45°: more realistic simulated point dataset, without the obvious geometric constraints of the square set.
- **Legumes of Madagascar.** 19,343 georeferenced records for 761 taxa, with species having from just one record up to 228 records (*Baudouinia fluggeiformis*), constrained to the island (Du Puy et al. 2002).
- ***Coffea* species of Africa.** 2,606 records for 58 taxa, covering a wide range of tropical/sub-tropical environments across many countries (Davis et al. 2006). Includes *Coffea arabica* (395 occurrence records).
- **Selected Caribbean endemics.** 899 records from 10 taxa. A set of Red List-assessed plant species useful for reviewing the outcomes from the different algorithms on a group of very

range-restricted, well-sampled taxa. Used to assess possible implications in terms of changes in threat status (Burton 2008; Royal Botanic Gardens Kew 2016).

All the real world datasets had been cleaned removing erroneous or highly inaccurately localities, these datasets were reprojected to the cylindrical equal area projection, in metres, based on the distribution of all of the point data, using the projection wizard in 'rCAT' (Moat 2017).

AOO algorithms

There is little guidance on the geometric needs of AOO measurements for RLS, other than to specify a regularly spaced, equal-area grid with a common origin (i.e. no individual cells floating, with different origins) (Resit Ackacaya, pers. comm. 2017) and a steer towards reporting in terms of 4 km² cells. We varied grid cell shape, origin and rotation to test for an optimal approach.

Cell shape: squares and hexagons. The most common cell and survey shape used in ecology is squares (Wheater et al. 2011), followed by circles (often used in forestry; de Vries, 1986) and rectangles. Circles do not tessellate, thus 'waste' area at their margins (21% more area than hexagons; Kershner, 1939) and rectangles are too variable: it would be possible to choose long, thin rectangles (transect-shaped) providing very small and unrealistic AOO for species with few occurrences. Squares give a simple and standardised fit, with straightforward mathematics, and represent the standard method used by many. Squares also match raster imagery's regular grids, which are often used to produce species distribution models (SDM), as well as habitat and vegetation maps. Hexagons are increasingly being used to describe and quantify distributions, their main advantages being to reduce edge/corner effects and having identical distances to neighbours (Birch et al. 2007). Hexagons were calculated with the R packages 'sp' (Pebesma & Bivand 2005) and 'lattice' (Sarkar 2008).

Grid origin: fixed, brute force and optimized. First, we tested the very simple default 'fixed origin' method, where the grid starts at 0,0 (using whatever projection is applied) (Moat 2007; Bachman et

al. 2011; Gilles et al. 2016; Cardoso 2017). Second, we tested a brute-force 'movable origin' method that iteratively moves the origin using a fixed number of positions, 1024 here (Schmidt *et al.*, 2017 used a simplified version of this method). Finally, we tested a 'movable origin (optimized)' method designed to produce the smallest possible AOO from a given set of points, from all possible positions of the origin (see Table 1).

Grid rotation: NSEW, brute force and optimised. In mapping/cartography, grids are predominately orientated in north–south/east–west (NSEW), a convention that mainly prevails for aesthetic reasons. We implemented three rotation methods for calculating AOO. Firstly, we tested NSEW - the grids were not rotated from their original orientation. Secondly, the 'multiple rotation (brute force)' method rotated the grid through 1024 iterations. Finally, the 'multiple rotation (optimised)' was designed to give the rotation that minimised the estimated AOO.

To keep results comparable and processing time reasonable, we restricted the number of iterations for the brute force methods to 1024, except for simulations that combined rotation and moving origin which was 1152 iterations (summarised in Table 1; examples shown in Figure 1).

Experimental design

We tested how occupancy density (the balance of cell size and the number of occurrence points) affected the outcome and range of values for AOO calculation. To do this, we ran the 'Movable origin (brute force)' algorithm with varying cell sizes and numbers of points, using 1024 combinations (iterations). For each combination, we recorded the average standard deviation.

To compare processing speeds of each algorithm, we recorded the time taken using 'proc.time' in the core R package (R Core Team 2016). Each method was timed using the same PC (Windows 7 PC, with Xeon 3.3 GHz processor, 8 cores, 64 Gb Ram and a SSD hard disk). We ran all methods except

the hexagons across a 5 × 5 grid, using 1–4000 points. As the optimal algorithms run exponentially, we curtailed these once the processing time exceeded 60 seconds.

We first tested the difference between AOO shape (squares vs hexagons) using a restricted set of algorithms, leading us to eliminate hexagons from further analysis. We then ran all the algorithms using square cells, for all the datasets, to test a wide range of point/cell densities. For both the oval and square sets of points we ran the algorithms with 10, 30 and 80 points across an area of 25 cells, representing sparse, medium (with maximum variability) and saturated sets of points, respectively. We ran a further set with 120 points with an area of 100 cells, to check that scale was not affecting results. For each of the simulated datasets, we ran 100 randomly generated datasets. For the real-world datasets, we do not have an optimal density for each (as they represent multiple species with different areas, multiple collection densities at multiple scales), but we wanted to use these to represent real-world distributions and shapes. For the legumes of Madagascar and the *Coffea* species of Africa, we used cell widths of 2000, 1000, 500 and 2 km (corresponding to 4,000,000, 1,000,000, 250,000 and 4 km^2 cell areas). For the well sampled, narrowly distributed endemic species of the Caribbean we used 2, 4, 8 and 16 km cell widths (4, 16, 64 and 256 km^2 cell areas). Our reasoning for a range of cell sizes (including RLS reference scale of 2 × 2km) was not only to test the actual IUCN recommended cell size, but to review the most optimal algorithms. For most species the sampling will be too low to allow an accurate calculation of AOO. These real-world datasets were included as they have the inherent bias and collection densities of real data, but at the cell sizes chosen we should see increasing variation in AOO values as we approach the optimal ratio of cells to points.

To determine which algorithms worked best, we calculated the number of times an algorithm produced the minimum AOO across all methods. For each, we also recorded the mean change in AOO compared to the simplest algorithm (square, fixed origin, NSEW). To further differentiate the

196 algorithms, they were ranked 1–6 (1 = highest number of times it equalled the minimum AOO) for
197 each dataset and scenario.

198 To assess the potential impact of the different algorithms on existing IUCN assessments, we
199 reviewed the prevalence of AOO reported in the latest version of the Red List (methods detailed in
200 Supporting Information). We queried the IUCN Red List (IUCN 2016a) for all Critically Endangered
201 (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT) and Least Concern (LC) species
202 (07/09/2016), using the IUCN API (IUCN 2016b) and the R package 'rredlist' (Chamberlain 2016).
203 Where a range of values or limits was given for AOO, we used a middle value.

204 # Results

205 ## Cell size and cell occupancy

206 Testing the number of points versus cell occupancy revealed that cell occupancy tended to follow a
207 binominal distribution (Figure 2A). The upper bound is where AOO equals all available cells
208 (saturation); the lower bound is where one point can only occupy one cell. We found maximum
209 variability in AOO at the cell to random point ratio of 1:1.21 (e.g. 121 points in 100 cells; Figure 2B) –
210 the ratio used within our point simulations to give the greatest variability (see Methods).

211

212 ## Which algorithms estimated the lowest AOO

213 Square cells always produced the lowest AOO estimates (Supporting information; Table S2). In the
214 real-world examples, the minimum AOO for hexagons only approaches that for squares when cells
215 become saturated with points, but the opposite happens for the simulated datasets, in which
216 hexagons improve at lower occupancy densities. For grid origin and rotation algorithms, all results
217 (Supporting information; Tables S2 and S3) are summarised in table 2, and figure 1 shows an
218 example graphic. The main findings (percentages quoted in brackets equals the percentage of runs
219 that the algorithm achieved the lowest AOO value) are:

Moving origin brute force vs optimized. The optimal always performed better (69%) than, or as well as, the brute force algorithm (62%).

Rotation brute force vs optimized. The brute force (60%) was as good as, in many cases better than, the optimized (59%). Optimized was only better at higher numbers of points, in which the number of iterations far exceeds the 1024 used for brute force.

Brute force, moving origin vs rotation. The moving origin gave the best results for the square set of points, but only at higher occupation densities (e.g. 80 points in 25 cells). In the other data sets, there was little difference between the two (moving origin 62% vs rotation 60%).

Combined methods: The combined brute force constantly performed well (average rank 1.8; with an average AOO reduction of 17%), often outperforming the combined optimized (average rank 1.5, average AOO with a reduction of 15%) for the average reduction in AOO. It should be noted that the optimized algorithm is restricted to running on datasets with ≤ 19 points, so this does not allow gains from the higher AOO reductions at higher numbers of points.

AOO reductions: In the real-world data, estimated AOO decreased by 3% to 32% compared with the standard method (square, fixed origin, NSEW), with smaller reductions tending to be associated with sparse occupancy. For the well-sampled Caribbean species, average AOO reduction was 22% to 28%.

Processing time

The hexagon algorithms were very slow; the processing time increases exponentially with the number of grids cells. All the square algorithms performed as expected from their number of iterations (Table 1). The processing time of the iterative algorithms increased linearly with the number of points, with the slightly more complex rotation and combined algorithms running a little slowly than the simpler moving origin (Figure 3A). The optimized algorithms became very slow with more than a few occurrence points, exceeding 60 seconds at 266, 190 and 19 points for rotation, moving origin and combined optimized algorithms respectively (Figure 3B).

Impact on existing Red List assessments

We examined 68,574 species on the IUCN Red List website (IUCN 2016a), 23% documented AOO in their extinction risk assessment (Supporting information; Table S4), but only those using the B2 criteria will have explicitly used AOO (A1c and D2 could have used AOO or other geographic metrics). It is very difficult to assess how many species use the AOO metric for their assessment, as not all species have an AOO measurement documented. We detail the results and issues in supporting information (text, table S4 and Figure S3). We estimate that 10,000–14,500 species use AOO within their assessment (15% to 21% of all species assessed). When reviewing species near thresholds (Supporting information; Figure S3), we estimated that approximately 3% of species using AOO within their assessment (~ 300 species), could be uplisted to a higher threat category (more threatened) by applying a minimum AOO algorithm.

Discussion

To-date there has been inconsistency in the method used to calculate the AOO of a species. Here we have shown that the estimated AOO was substantially reduced (by as much as 40%, or even more for small extents, e.g. 80%, from 5 cells to 1 cell) by modifying the origin and rotation of the grid system, compared with the commonly applied algorithm. Reviewing already assessed species we estimate that about 300 species may have been placed in a less-threatened category than they should have during the IUCN Red List assessment procedure. The new algorithm that we propose (combined moving origin and rotational brute force) should overcome this issue, providing more accurate AOO estimates and running quickly on standard computers. The proposed algorithm can also be applied to analogous operations which involve area estimation from point data.

AOO Algorithms

In isolation, changing rotation (average rank 3.6) and changing origin (average rank 3.5) had similar effects on AOO estimation, except that in some of the real-world data, rotation produced a small advantage. This is likely due to the rounding of latitudes and longitude (to the nearest minute or decimal place), which would place more points along the latitude and longitude axes, where a diamond square (square rotated 45° from NSEW), would have more 'reach' to gather points. Combining rotation and moving origin gave the best results (average rank of 1.8), even with the same number of iterations. As expected, the optimized algorithm for the moving origin always gave better or the same results as the brute force algorithm, and we can be confident that this is the optimal solution for moving origin. We applied the same logic to optimizing rotation, rotating the grid to all the possible point pairs, but we found that this did no better than the brute force solution. This suggests that our optimization for rotation can be improved; this would benefit from further research. So, would the issue of the quality of input data (in our case the rounding and accuracy of point data) and its influence on AOO and EOO.

Given unlimited time and processing power, combining optimizing algorithms for moving origin and rotation should produce optimal results. However, for any algorithm to be useful, it should be responsive (run quickly), robust and reproducible. The optimizing algorithms for rotation and moving origin quickly become untenable, even with small numbers of points, producing a vast number of iterations (1 million computations for 38 points in the combined optimization). We quantitatively compared results for datasets with relatively low numbers of points. For those, the combined iterative ('brute force') approach with 1152 iterations achieved the minimum AOO 83% of the time across all our test data and 96% for the real-world datasets (Supporting information, Table S3), and was almost always very close. This is despite the large shortfall in number of iterations (1152 for brute force vs. up to the equivalent of 65,000 iterations for optimal). The Caribbean dataset was the only dataset with sufficiently well-sampled point data to fully test the influence of algorithm choice on real AOO values, the combined brute force algorithm with 1152 iterations only achieved the

minimum AOO for 50% of the taxa, compared to the optimal algorithms. To further investigate this using a fairer test, we randomly placed 10 points in 8 cells and ran both the optimization algorithm (which required the equivalent of 4500 iterations) and the combined brute force algorithm with 4500 iterations. We ran this equal-effort procedure 100 times; the brute force algorithm achieved minimum AOO 98% of the time, compared to 84% for the optimization algorithm.

We therefore recommend using the combined brute-force algorithm, with minimum of 1152 iterations, as a good compromise between time taken and quality of results. If minimum AOO is critical (particularly where a taxon is close to a threshold), then we recommend an increase in iterations – and suggest the upper limit is would approach 100,000. This approach has the additional advantage that AOO can be fully quantified by giving the spread of AOO values (mean, mode and maximum) as well as the minimum, in line with IUCN guidelines to document uncertainty (IUCN Standards and Petitions Subcommittee 2016).

Hexagon grid shapes never out-performed squares and ran slowly with even small numbers of cells. Square cells have the advantage of requiring very simple mathematics, being highly applicable to ground surveys and being directly analogous to raster data. For the application of minimum AOO, square cells are a clear winner.

For our simulations, we have assumed that these data represent well-sampled taxa or ecosystems. This assumption will make little/no difference for our testing but will be critical for actual species assessment using AOO. It is in these cases that the impact of previous calculations of AOO (or their non-usage) is particularly important. Overlooking the modifiable areal unit problem has important implications for the conservation of many species.

Impact of findings on the IUCN Red List of Species

We estimated from documented AOO values on the IUCN website that 3% of species may be affected by improving AOO estimation methodology. This is a reasonable, if slightly high, estimate because additional sub-criteria such as number of locations also need to be fulfilled to warrant a

category change (IUCN Standards and Petitions Subcommittee 2016). Of greater significance is the impact AOO estimation methods will have on the unknown, but very large number of species, yet to be assessed using the IUCN criteria. For our well-sampled Caribbean species, applying the new algorithms reduces estimated AOO by 22% to 28%, giving some indication of the likely implications of applying the changed methodology to the present Red List for species with AOO of about 250 km^2 or less (which would qualify for the EN or CR categories). It would seem prudent to give a range of values for AOO (as practically, at the thresholds, they are very sensitive to small changes in number of cells which would lead to changes in extinction risk assessment). Such a range allows the user to determine how far a threshold has been exceeded. We also suggest that automated techniques, such as described here, can be used as a first pass and then updated/adjusted by experts, particularly if close to a threshold.

To demonstrate how critical the AOO methods of measurement can be, we applied the combined brute force algorithm to the Caribbean plant species *Spermacoce capillaris* (Figure 4). This species is endemic to the Turks and Caicos Islands, has a very small geographic range (both AOO and EOO), and is experiencing continued decline due to habitat loss/degradation. It is assessed as Endangered under B1 and B2 criteria (Endangered B1ab (ii,iii,v)+2ab (ii,iii,v)) (Barrios & Manco 2014). Its documented range (AOO), calculated using GeoCAT (Bachman et al. 2011), is 16–52 km^2, where the higher estimate uses both inferred and observed occurrences of the species (total = 19) and the lower only uses the observed (and verified) records. Applying the combined brute force algorithm (Figure 4) reduces the lower AOO to 12 km^2 (25% lower) and the higher one to 36 km^2 (33% lower than the documented value). In this example, the reduction in AOO estimate does not result in a change in the rating, but it does bring the minimum estimate much closer to the threshold for 'Critically Endangered' (10 km^2). Clearly, in many cases an equivalent change would change a threat rating.

Moreover, using the 19 observed and inferred occurrences, the range of AOO values across the iterations is 36–60 km² (Figure 4A). Thus, some arrangements of cells of the same size give AOO 66% higher than others, highlighting how important it is to run algorithms to minimize the AOO estimate. Equivalently, if AOO is calculated over different time points, for example to calculate change over time (RLS criteria A1-4c; IUCN 2012), the vagaries of grid cell placement could easily give a false indication of reduction or expansion of an AOO purely as an artefact of methodology.

Concluding remarks and recommendations

We have presented some very simple, yet powerful, methods and algorithms for calculating AOO based on a set of points. As computing power increases, and with improved algorithms, optimized solutions may become a more viable method for estimating AOO, which would be desirable for conservation. For at least the present, we recommend using the combined brute force method presented here. We have also shown that hexagons rarely give optimal (minimum) results and are computationally demanding; we advise against using them for AOO calculations. We tested our methods with example species (relevant to RLS) but not ecosystems (RLE); from preliminary analysis using moist Afromontane forest in Ethiopia at 30 m resolution (Supporting information, Figure S4), which shows as RLS a binomial distribution, we expect our findings to be as applicable to RLE as to RLS. We demonstrate that a small percentage (3%) of species presently assessed on the IUCN Red List may have AOO estimates that are too high. It would seem needless to reassess most of these species, but we recommend the following procedure for future application of AOO with both RLS and RLE:

1. Apply the suggest algorithm: combined moving origin and rotational brute force algorithms with a default of 1,152 iterations. This can be increased if the AOO is close to a threshold or if a minimum value AOO is critical.

2. Record summary statistics across the iterations of AOO estimates (minimum, maximum, mean, mode) and the method and grid shape used to calculate AOO, as well as the original occurrence data.
3. Record the angle of rotation and origin for the minimum AOO. This is important for reproducibility, but also for any analysis looking at temporal changes in AOO.
4. For species recorded in latitude and longitude, use an equal area projection (Moat 2017) and record the mapping projection, shift and datum used (Wieczorek et al. 2012).

Using *Spermacoce capillari*s (Figure 4) as an example, our recommendation for reporting is:

> *Spermacoce capillari*s AOO: 12 km^2 (using 1152 iterations for verified records, minimum = 12 km^2, maximum = 28 km^2, mean = 18.8 km^2, mode = 20 km^2, method= combined moving origin and rotational brute force using square cells. For minimum AOO estimate, rotation = -78.3873 °, grid origin = (0,0), map projection = Cylindrical Equal Area with central meridian: longitude -71.51022, latitude 21.53104, Datum=WGS84.)

The method we present here has been tested with point data and, in the main, assessed for RLS, but the findings and algorithms can also be used for the Red List of Ecosystems, easily transferred to MAUP and other analogous situations (e.g. SDM and raster imagery). We have shown that our combined brute force AOO algorithm is quick and robust, and hope that our recommendations will be implemented in the IUCN RLS and RLE guidelines. We would like to encourage the increased uptake of AOO within the community and beyond.

Supporting information

Supporting text, figures (S1, S2, S3 and S4) and tables (S1, S2, S3 and S4) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Code

All scripts in R and simulated data are freely available in the lead author's GitHub account: https://github.com/#####

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Tables

Shape, Method	Number of iterations	Algorithm
Square, fixed origin, NSEW	1	Unique(floor(SetofPoints/CellSide))
Square, moving origin (brute force), NSEW	1024	As above moving points dx and dy. Where dx and dy = 0 to cell width with 32 steps (total iterations of 32^2 = 1024)
Square, moving origin (optimized), NSEW	n^2	As above, but where dx = difference between each point and every other point in dx and dy = difference between each point and every other point in y and x
Square, fixed origin, brute force rotation	1024	Rotating points between 0:1.5708 (radians) with 1024 steps
Square, fixed origin, optimized rotation	$\frac{(n^2 - \mathrm{n})}{2}$	As above, but rotations are between each point and every other point

Square, brute force origin and rotation	1152	Combining rotation and moving origin, with 6 shifts in x and y and 32 rotations (6^2 x 32 = 1152)
Square, optimized origin and rotation	$\frac{(n^4 - n^3)}{2}$	Optimal rotation and moving origin algorithms combined
Hexagon, fixed origin, NSEW	1	Build hexagons across region. Overlay points and hexagons, unique count of hexagons
Hexagon, moving origin (brute force), NSEW	1024	As above moving hexagons dx and dy. Where dx and dy = 0 to cell width with 32 steps (total iterations of 32^2 = 1024)

*Table 1. Methods used to calculate AOO, number of iterations and algorithm description. * n = number of points in the test dataset or number of points representing the species. NSEW = north–south/east–west orientation.*

Data type, scenario	Number of runs	Moving origin: brute force	Rotation: brute force	Combined: brute force	Moving origin: optimal	Rotation: optimal	Combined: optimal
Simulated: square, area of 25 cells: 10 points	100	5	3	2	4	6	1
Simulated: square, area of 25 cells: 30 points	100	3	3	1	2	5	
Simulated: square, area of 25 cells: 80 points	100	2	5	3	1	4	
Simulated square, area of 100 cells: 120 points	100	5	4	1	2	3	
Simulated: oval, area of 25 cells: 10 points	100	4	5	2	3	6	1
Simulated: oval, area of 25 cells: 30 points	100	3	4	1	2	5	
Simulated: oval, area of 25 cells: 80 points	100	3	5	1	2	4	
Simulated: oval, area of 100 cells: 120 points	100	3	5	1	2	4	
Legumes of Madagascar: cell size 4 km^2	1435	5	3	2	4	6	1
Legumes of Madagascar: cell size 250,000 km^2	1435	5	3	1	3	6	2
Legumes of Madagascar: cell size 1,000,000 km^2	1435	4	4	1	3	6	2
Legumes of Madagascar: cell size 4,000,000 km^2	1435	1	1	1	1	6	1
Coffea of Africa: cell size 4 km^2	58	6	2	3	5	3	1
Coffea of Africa: cell size 250,000 km^2	58	1	6	4	1	5	3
Coffea of Africa: cell size 1,000,000 km^2	58	1	6	3	1	5	3
Coffea of Africa: cell size 4,000,000 km^2	58	1	5	1	1	6	4
Caribbean taxa: cell size 4 km^2	10	6	2	4	5	3	1
Caribbean taxa: cell size 16 km^2	10	6	3	4	5	1	1
Caribbean taxa: cell size 64 km^2	10	6	4	1	5	1	1
Caribbean taxa: cell size 256 km^2	10	5	1	1	6	1	1
Summary (total, mean)	6812	3.6	3.5	1.8	2.7	4	1.5

*Table 2. Summary ranking of Algorithms lowest AOO achieved. * Ranking of Algorithms from best (1) to worst performing (5 or 6). For details see supporting information table S3. NB we allow the optimal algorithms to run up to 60 seconds, which gives the equivalent of ~ 62,000-71,000 iterations vs brute force algorithms of 1,024 or 1,152 iterations.*

Figures

Figure 1. AOO example shapes and algorithms, using 30 random points in a square (of size 10 x 10 km in the x and y direction) and cell size of 4 km². Number of occupied cells is given in the top-right of each example. Algorithms (left hand side) are: worst case = highest number of occupied cells when running the brute force algorithm; initial case = simplest algorithm (square, fixed origin, NSEW); iterative best case = lowest number of occupied cells for the brute force algorithm; optimal best case = lowest number of occupied cells using the optimizing algorithm. Details of the algorithms are given in Table 1

Figure 2. A. Example histograms for numbers of cells occupied, with 1024 iterations, for each of 3, 10, 30, 80 and 200 occurrence points spread over 25 cells. B. For each number of points shown, the number of cells for which the mean Standard Deviation was highest (from 100 runs of the brute force algorithm with 1024 iterations) is plotted.

Figure 3. Algorithm time taken vs number of points in test dataset. A. Iterative 'brute force' algorithms; B. Optimizing algorithms. Note the different scales in A and B, on both axes.

Figure 4. Maps and AOO ranges for *Spermacoce capillaris*. A = All records (inferred and known), mode of 1152 iterations using combined brute force algorithm = 12 cells (48 km²), mean = 11.74 (47 km²), maximum= 15 (60 km²) and minimum = 9 (36 km²). B= All known records, mode of the 1152 iterations = 5 cells (20 km²), mean = 4.7 (19 km²), maximum= 7 (28 km²) and minimum = 3 (12 km²).

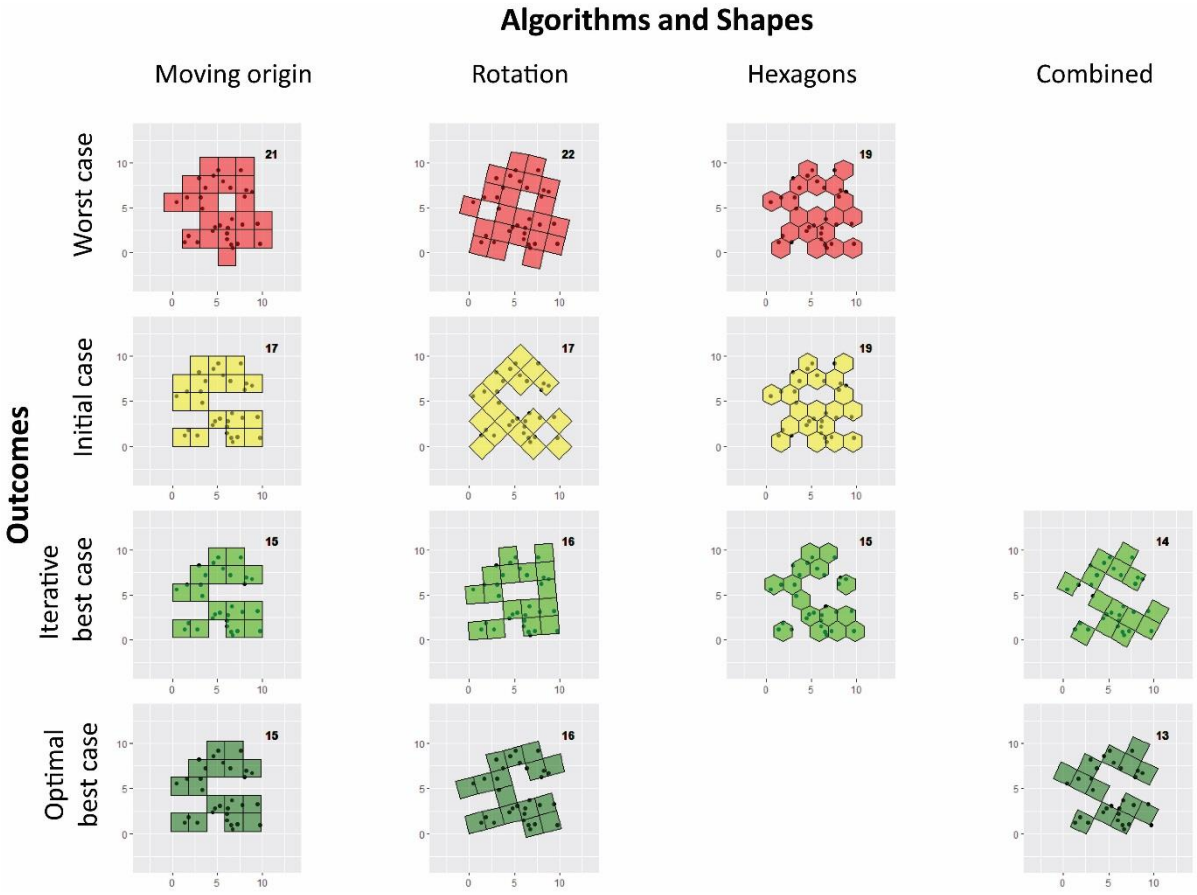


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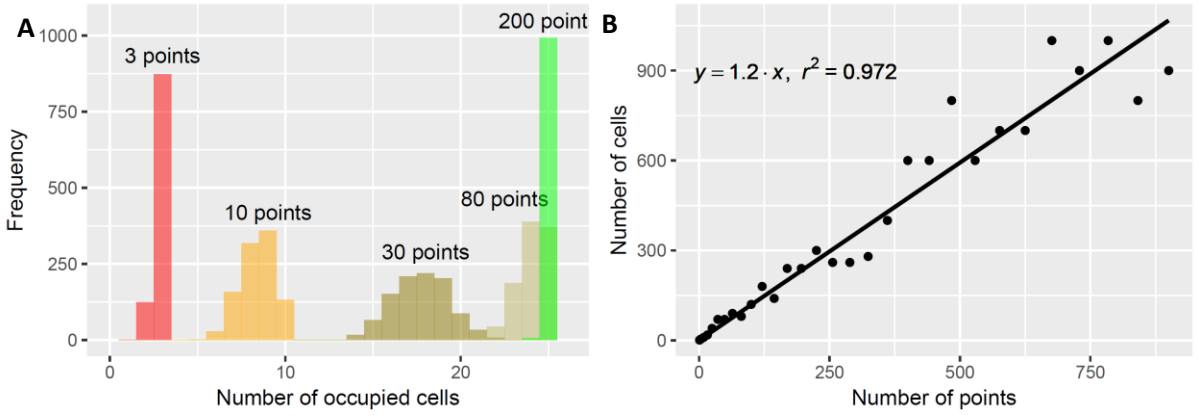
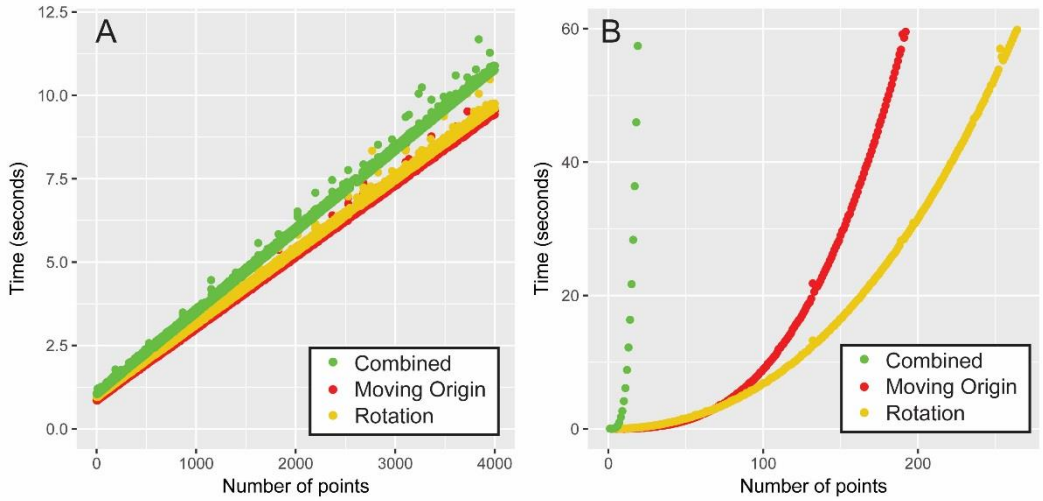


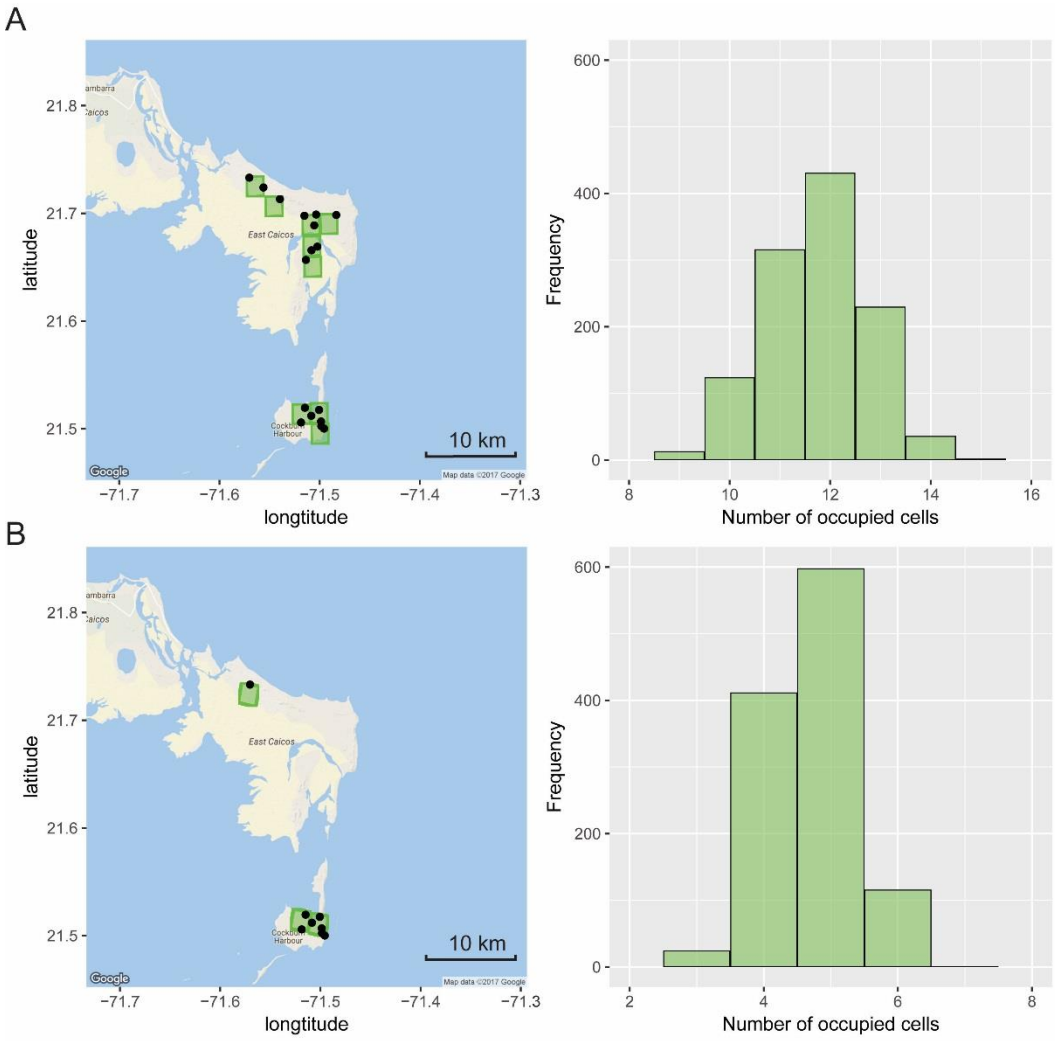
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511

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514



515

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517 *mode of 1152 iterations using combined brute force algorithm = 12 cells (48 km²), mean = 11.74 (47 km²), maximum= 15*

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Addressing the modifiable areal unit problem in ecology and conservation: refining area of occupancy (AOO) for extinction risk assessment.

Supporting information

Supplementary Text

Detailed results on the Effects on existing Red List assessments (See table S4 and figure S2)

Of the 68,574 species in the IUCN Red List website (IUCN 2016b), 23% could have used AOO in their extinction risk assessment (Table S2), but only those using the B2 criteria will have explicitly used AOO (A1c and D2 could have used AOO or other geographic metrics). Unfortunately, it is very difficult to assess how many species use the AOO metric for their assessment, and therefore may be affected by changes in AOO methodology. This is because not all species have an AOO metric documented (any species with criterion B2 should use AOO, but of those listed only 44% have a AOO value documented; Table S2). Nevertheless, we estimate that the bound is approximately 10,000 species (species with criterion B2 plus those with D2 and an AOO quoted), which is approximately 15% of the species on the IUCN red list. We estimate the upper limit at around 14,500 species (Table S2: 9742 + 4705 + 2), or approximately 21% of the species on the IUCN red list.

We also queried the IUCN Red List (IUCN 2016b) for all species with a documented AOO value: 8,743 species were listed, but it should be noted that many assessments will not have relied strictly on AOO for the final rating. Notably, most species with documented AOO values are endangered, critically endangered and/or have AOO close to a threshold defined by the IUCN criteria (Figure S3).

From these findings, we estimated the number of species whose listed threat status could be affected by applying an improved AOO algorithm, by reviewing those species with documented AOO just above the category thresholds (Figure S3, Table 1). Doing so, we estimate that approximately 300 species (~3% of the total Red-Listed) could be changed to a lower threat category (more

threatened) by apply minimum AOO algorithms. Note that many of these 300 species may retain the higher threat category because other criteria such as number of locations need to be met at the lower threshold to fulfil the requirements of a rating change, In addition, many species have no AOO documented (older assessment) or may have not been assessed using AOO.

Supplementary tables

Risk Category	**AOO RLS (km^2)**	**AOO RLE (km^2)**	**RLS No. of presence cells for (2x2 km)**	**RLE No. of cells presence (10x10 km)**
Critically Endangered (CR)	<10	<= 200	<=2	<=2
Endangered (EN)	<500	<= 2,000	<=125	<=20
Vulnerable (VU)	<2,000 (<20[1])	<= 50,000	<=500	<=50
Near Threatened (NT)	<3,000[2]	NA	<=750[2]	NA

Table S1. AOO Thresholds used in IUCN Red List of species (RLS) and IUCN Red List of Ecosystem (RLE) assessments [1] These thresholds are used for very restricted species, using criteria VU D2 [2]This is a guideline value NT does not have a specific value, D2

Data type, scenario	**Number of runs**	**Hexagons (equal to minimum)**	**Square (equal to minimum)**
Simulated: square, area of 25 cells: 10 points	100	58%	100%
Simulated: square, area of 25 cells: 30 points	100	13%	100%
Simulated: square, area of 25 cells: 80 points	100	0%	100%
Simulated square, area of 100 cells: 120 points	100	0%	100%
Simulated: oval, area of 25 cells: 10 points	100	43%	100%
Simulated: oval, area of 25 cells: 30 points	100	9%	100%
Simulated: oval, area of 25 cells: 80 points	100	0%	100%
Simulated: oval, area of 100 cells: 120 points	100	0%	100%
Legumes of Madagascar: cell size 250,000 km^2	1435	87%	100%
Legumes of Madagascar: cell size 1,000,000 km^2	1435	97%	100%
Legumes of Madagascar: cell size 4,000,000 km^2	1435	100%	100%
Coffea of Africa: cell size 250,000 km^2	58	64%	100%
Coffea of Africa: cell size 1,000,000 km^2	58	76%	100%
Coffea of Africa: cell size 4,000,000 km^2	58	86%	100%
Caribbean taxa: cell size 4 km^2	10	50%	100%
Caribbean taxa: cell size 16 km^2	10	70%	100%
Caribbean taxa: cell size 64 km^2	10	70%	100%
Caribbean taxa: cell size 256 km^2	10	100%	100%
Summary	**6,812 (total)**	**51% (mean) 81% (weighted)**	**100% (mean) 100% (weighted)**

Table S2. Percentage equalling the AOO minimum, hexagon cell shapes vs square cell shapes. For each scenario, percentages are the number of times that Hexagons or Squares achieved the lowest number of cells, divided by the number of runs. For simulated scenarios, this is the lowest AOO from 1,024 iterations across the simulated data. Summary includes mean percentage across all datasets/scenarios and mean percentage weighted by number of runs.

Data type, scenario	Number of runs	Moving origin: brute force	Rotation: brute force	Combined: brute force	Moving origin: optimal	Rotation: optimal	Combined: optimal*
Simulated: square, area of 25 cells: 10 points	100	38% : 14%	50% : 16%	86% : 20%	43% : 15%	29% : 13%	93% : 21%
Simulated: square, area of 25 cells: 30 points	100	29% : 11%	29% : 12%	86% : 16%	37% : 12%	25% : 11%	
Simulated: square, area of 25 cells: 80 points	100	74% : 2%	53% : 1%	67% : 2%	85% : 3%	55% : 1%	
Simulated square, area of 100 cells: 120 points	100	17% : 7%	30% : 7%	63% : 8%	43% : 8%	32% : 8%	
Simulated: oval, area of 25 cells: 10 points	100	49% : 20%	33% : 18%	92% : 26%	53% : 21%	27% : 17%	97% : 26%
Simulated: oval, area of 25 cells: 30 points	100	39% : 18%	21% : 15%	90% : 22%	51% : 20%	19% : 15%	
Simulated: oval, area of 25 cells: 80 points	100	38% : 13%	23% : 12%	86% : 16%	44% : 14%	24% : 12%	
Simulated: oval, area of 100 cells: 120 points	100	23% : 11%	14% : 10%	73% : 13%	51% : 12%	18% : 10%	
Legumes of Madagascar: cell size 4 km^2	1435	90% : 3%	94% : 3%	95% : 3%	91% : 3%	88% : 2%	97% : 3%
Legumes of Madagascar: cell size 250,000 km^2	1435	87% : 23%	88% : 23%	99% : 26%	88% : 23%	81% : 20%	96% : 20%
Legumes of Madagascar: cell size 1,000,000 km^2	1435	91% : 25%	91% : 25%	100% : 28%	92% : 25%	86% : 23%	97% : 21%
Legumes of Madagascar: cell size 4,000,000 km^2	1435	100% : 32%	100% : 32%	100% : 32%	100% : 32%	94% : 29%	100% : 24%
Coffea of Africa: cell size 4 km^2	58	79% : 6%	93% : 7%	91% : 6%	85% : 6%	91% : 6%	98% : 7%
Coffea of Africa: cell size 250,000 km^2	58	100% : 10%	72% : 1%	95% : 8%	100% : 10%	73% : 0%	98% : 6%
Coffea of Africa: cell size 1,000,000 km^2	58	100% : 11%	72% : 0%	98% : 11%	100% : 10%	76% : 0%	98% : 8%
Coffea of Africa: cell size 4,000,000 km^2	58	100% : 12%	76% : 0%	100% : 12%	100% : 13%	75% : 0%	93% : 5%
Caribbean taxa: cell size 4 km^2	10	30% : 18%	60% : 23%	50% : 22%	44% : 18%	56% : 19%	100% : 23%
Caribbean taxa: cell size 16 km^2	10	50% : 21%	80% : 26%	70% : 26%	67% : 24%	100% : 28%	100% : 23%
Caribbean taxa: cell size 64 km^2	10	70% : 26%	90% : 28%	100% : 28%	78% : 27%	100% : 28%	100% : 20%
Caribbean taxa: cell size 256 km^2	10	90% : 26%	100% : 27%	100% : 27%	89% : 23%	100% : 24%	100% : 17%
Summary (mean)	**6,812 (total)**	**62% : 15%**	**60% : 14%**	**83% : 17%**	**69% : 15%**	**59% : 13%**	**91% : 15%**

*Table S3. Algorithms lowest AOO value achieved. Winners (i.e. finding lowest AOO solution) for all square methods. First percentage equals the number that method equalled the minimum AOO across all methods): second percentage equals the average AOO difference between method and the initial AOO (at 0,0). * = Due to run away processing time, combined optimal was not run when number of point was great that 19 points, moving origin optimal 190, and rotational optimal 260. This reduced the number of runs for combined optimal to 49,572 runs (i.e. this only run with this the following number of species: legumes 1104, coffee 40 and Caribbean 4), both the rotational optimal and origin shift optimal to approximately 36,300 runs (legumes 1,435, coffea 55 and Caribbean 9).*

Criteria	Number of species using criteria	% of total	Number of species with documented AOO
A1c	1441	2.1	2
B2	9742	3.7	4266
D2	4705	6.9	741

*Table S2. Summary of Species assessed using AOO criteria. * A1c and D2 may use the AOO metrics, but also may use other metrics (i.e. A1c can use AOO, EOO or habitat and D2 AOO or number of locations).*

Supplementary figures

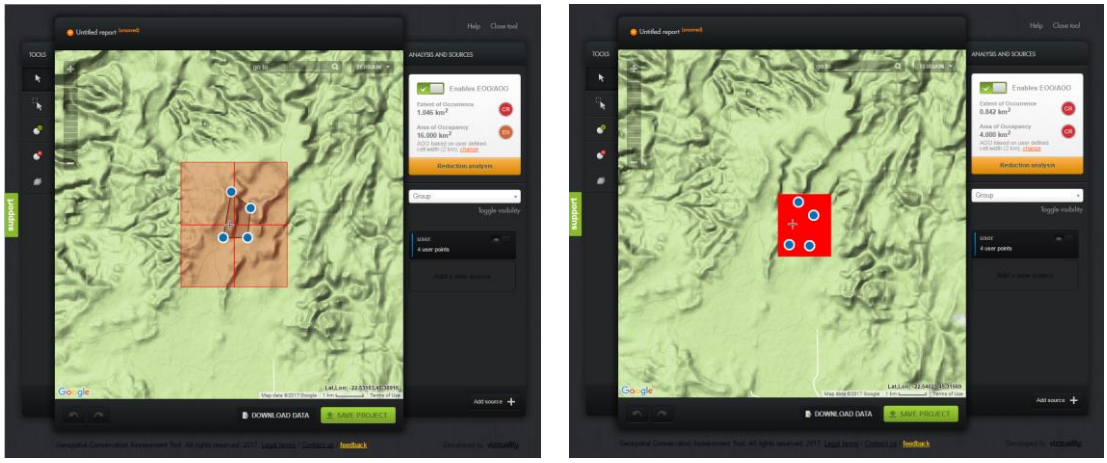


Figure S1. Example area of occupancy (AOO) calculation from GeoCAT (Bachman *et al.* 2011). *In this example, simply moving the origin of the grid cell system changes AOO fourfold, from 4 cells to 1 cell. This simple change would alter the resulting threat assessment from Endangered to Critically Endangered.*

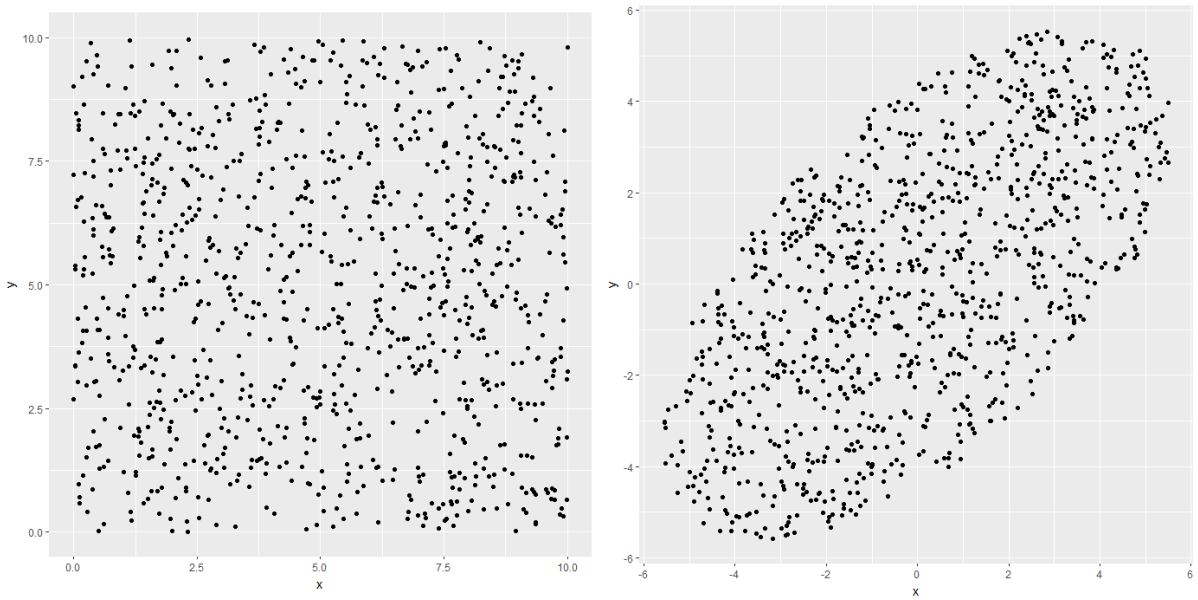


Figure S2. Simulated point data sets (1000 points). Left: square set of random points. Right: Oval set of random points

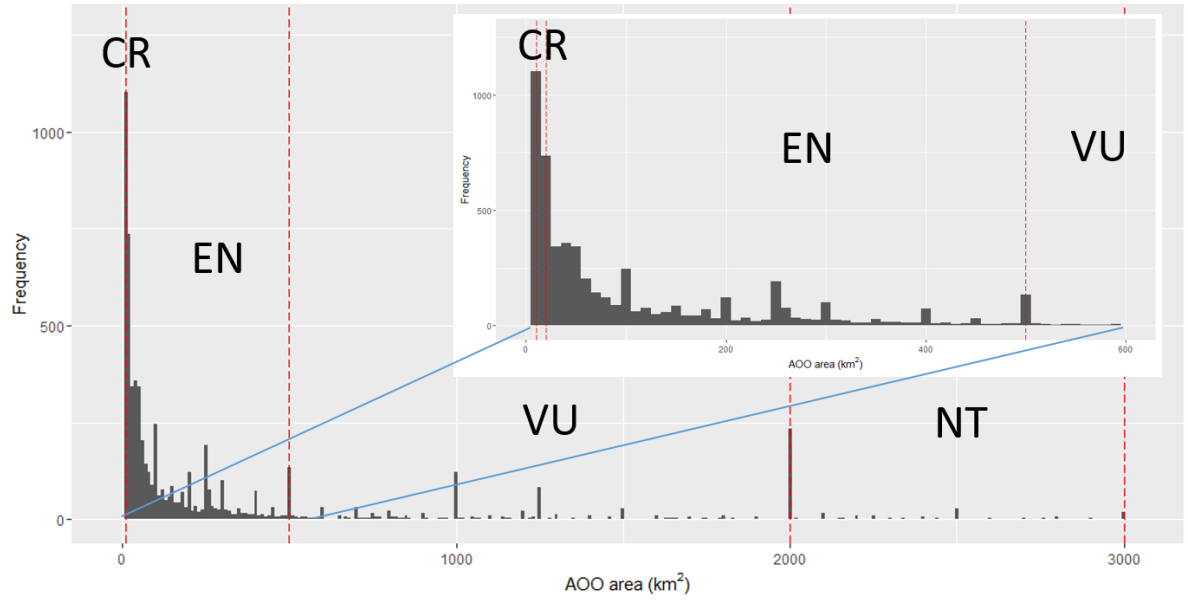


Figure S3. Histograms of AOO area. Retrieved from IUCN Red List. Insert top right show enlargement of the 0 - 600 km2 region. Red dotted lines are the IUCN thresholds for species categories

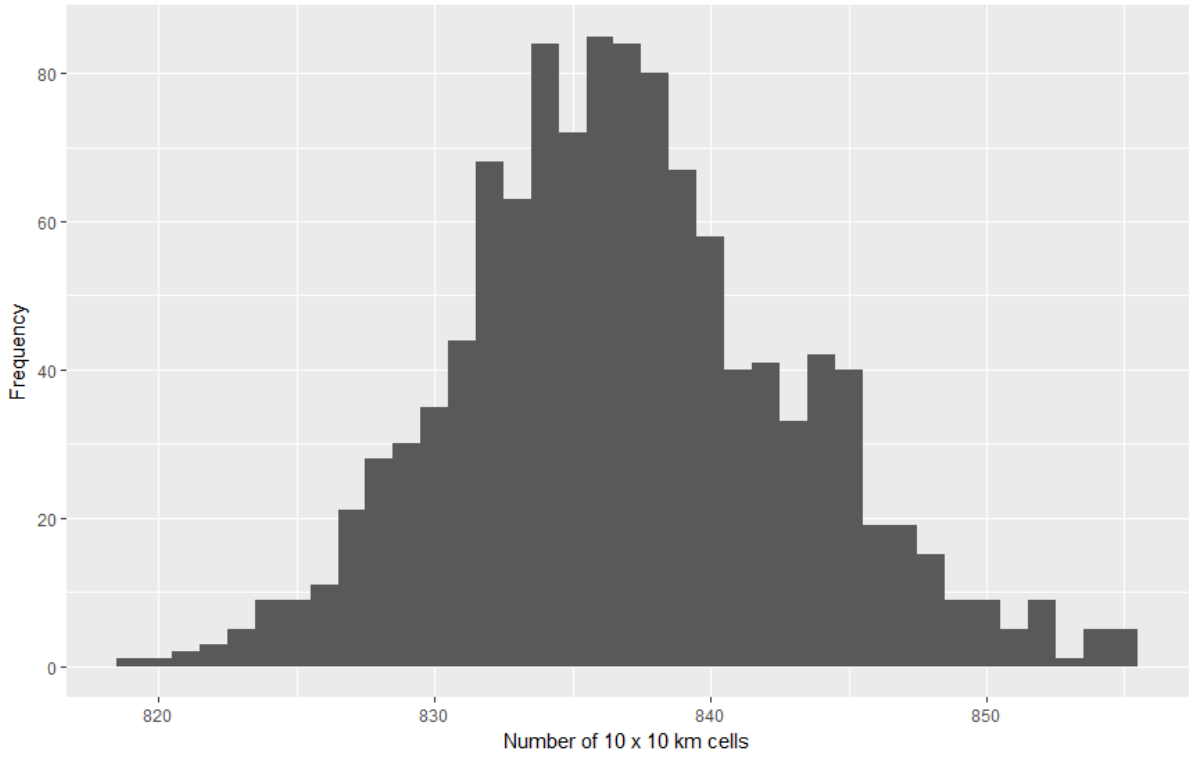


Figure S4. Histograms of AOO, number of cells for example RLE (moist Afromontane forest of Ethiopia), using brute force algorithm with 1024 iterations.

Paper VII. Least Concern to Endangered: applying climate change projections profoundly influences the extinction risk assessment for wild Arabica coffee

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Abstract

Arabica coffee (*Coffea arabica*) is a key crop in many tropical countries and globally provides an export value of over US$13 billion per year. Wild Arabica coffee is of fundamental importance for the global coffee sector and of direct importance within Ethiopia, as a source of harvestable income and planting stock. Published studies show that climate change is projected to have a substantial negative influence on the current suitable growing areas for indigenous Arabica in Ethiopia and South Sudan. Here we use all available future projections for the species based on multiple general circulation models (GCMs), emission scenarios and migration scenarios, to predict changes in Extent of Occurrence (EOO), Area of Occupancy (AOO) and population numbers for wild Arabica coffee. Under climate change alone, our results show that population numbers could reduce by 50% or more (with a few models showing over 80%) by 2088. EOO and AOO are projected to decline by around 30% in many cases. Furthermore, present-day models compared to the near future (2038), show a reduction for EOO of over 40% (with a few cases over 50%), although EOO should be treated with caution due to its sensitivity to outlying occurrences. When applying these metrics to extinction risk, we show that the determination of generation length is critical. When applying the International Union for Conservation of Nature's

Red list of Threatened Species (IUCN Red List) criteria, even with a very conservative generation length of 21 years, wild Arabica coffee is assessed as Threatened with extinction (placed in the Endangered category) under a broad range of climate change projections, if no interventions are made. Importantly, if we do not include climate change in our assessment, Arabica coffee is assessed as Least Concern (Non-threatened) when applying the IUCN Red List criteria.

Introduction

For the 2015/2016 coffee harvest period, c. 4.3 million tonnes (71.93 million 60 kg bags) of Arabica coffee (*Coffea arabica*) were exported globally, with an estimated export value of US$ 13.8 billion (based on a composite price of US$1.46 per lb) (International Coffee Organization (ICO), 2017). The export value of Arabica coffee is an important, and in some cases critical, component in the economies of several tropical countries (International Coffee Organization (ICO), 2017). Global consumption of coffee (including robusta coffee: *C. canephora*) has had an average annual growth rate of 1.3% since 2012/13 (International Coffee Organization (ICO), 2016, 2017).

Despite being a globally distributed tropical crop, wild populations of Arabica are restricted to the humid forests of Ethiopia, and a small area of neighbouring South Sudan (Figure 1) (Davis *et al.*, 2012). These wild populations have considerable value as the main storehouse of genetic resources for Arabica coffee (Davis *et al.*, 2012), and have provided fundamental resources for Ethiopia and the global coffee sector (Hein & Gatzweiler, 2006). In Ethiopia, these genetic resources continue to provide an important source of new planting material for coffee-farming, via seed and seedlings, including disease resilience variants, and the intrinsic (genetic) variation associated with the various flavour profiles found across the coffee landscape. Historically, and in recent times, wild Arabica coffee has provided germplasm for the development of the Arabica coffee sector outside Ethiopia. Protection of wild populations of Arabica coffee is therefore viewed as a key part of the long-term sustainability strategy for Ethiopian coffee production and the global coffee sector (Hein & Gatzweiler, 2006).

Despite the importance of wild Arabica populations in Ethiopia and South Sudan, there are serious threats to the survival and genetic integrity of this species. Amongst the most serious of these threats are deforestation (Davis *et al.*, 2012, 2018; Moat *et al.*, 2017a), climate change (Davis *et al.*, 2012; Moat *et al.*, 2017a, 2017b) and genetic erosion (Aerts *et al.*, 2012). Recorded climate data in Ethiopia from the 1960s onwards shows an average increase in the mean annual temperature of 0.28 °C per decade (Jury & Funk 2013), a shortening of the wet season, and an increase in the number of hot days (McSweeney *et al.*, 2010). Given the scale, severity and potential impact of these threats and other negative influences it is important that the extinction risk of wild Arabica coffee is

comprehensively assessed. Until now, no formal extinction risk assessment has been made for Arabica coffee.

The International Union for Conservation of Nature's Red list of Threatened Species (the IUCN Red List (IUCN 2012)) is a global repository of species and their associated risk of extinction (Rodrigues *et al.*, 2006). The IUCN Red List is recognised as the most authoritative source on extinction risk; it is widely used and cited, and conservation decisions and actions are increasingly informed by the resulting species-level risk assessments. One of the IUCN Red Lists' main roles is as an 'early-warning' system for species that are have the most imminent risk of extinction, therefore informing priorities for conservation action (Vié *et al.*, 2009; Keith *et al.*, 2014).

The central process of assessing extinction risk for a species is the assignment to one of nine categories, which are based on five criteria associated with extinction risk: population decline; geographic distribution; small population size; restricted populations and quantitative analysis of extinction risk (IUCN, 2012).

Within this study we review and address the first four criteria, using: past, present-day and future projections (based on the projection of accurate present-day occurrence (generated from species distribution models (SDMs), using precise ground-point data, and remote sensing of suitable forest type) under various climate change scenarios (Davis *et al.*, 2012; Moat *et al.*, 2017a); combined with demographic and generation length information. We apply three metrics for the present-day and future occurrence (under climate change): (1) Extent of Occurrence (EOO), a measure of risk spread (Gaston, 1991, 1994, 2012), using a minimum convex polygon enclosing all known localities (as recommend by (Joppa *et al.*, 2016). (2) Area of Occupancy (AOO), a measure of geographic range size (Gaston, 1991, 1994; Gaston & Fuller, 2009), which for the simplest calculation is the number of 2 x 2 km cells a species occupies (Moat, Bachman, Fields and Boyd 2018, in press). (3) Population size, which is estimated from the SDMs, forest cover (from remote sensing), population demographics and the quality of the niche.

The analyses we present here are focused primarily on exposure (i.e. to climatic suitability), based on climate scenario projections from GCMs. Other aspects of climate change vulnerability, viz. sensitivity and adaptive capacity (Dawson *et al.*, 2011; Foden & Young, 2016), are not directly addressed, although Arabica coffee is identified as a climate-sensitive species with a low adaptive capacity (Davis *et al.*, 2012).

Species distribution models (SDMs) have been widely used in conjunction with other modelling methods to make projections for the potential impact of climate on species ranges (Elith & Leathwick, 2009; Franklin, 2010). As well as giving a prediction for a species range, SDMs can also provide key information on the fundamental biology and ecology of a species. SDM techniques have matured considerably over the last 15 years or more, particularly with the introduction of ensemble modelling approaches (Araujo & New, 2007; Thuiller *et al.*, 2009, 2014). Predicting climate change with certainty is impossible, but we can use multiple models and scenarios to project future trends for

species: by comparing the results from these models, we can start to understand the vulnerability of species to climate change and overall trends, at least in terms of exposure. If all models point to a similar (or the same) outcome we can be increasingly confident in our projections. Within this study we calculate EOO, AOO and population estimates for Arabica coffee using multiple scenarios and models for climate and migration (Table 1), and then quantify these for the past, present and future.

Methods and materials

Overview

Three major spatial datasets where used in our analyses; observational (geo-located) ground-point data, species distribution models (SDMs) (which cover present-day to future, under various climate change scenarios and multiple general circulation models (GCMs)), and forest cover (from remote sensing (Moat *et al.*, 2017a; Davis et al., 2018). The SDMs were combined with forest cover and integrated into a 1 km^2 grid for further analysis. Generation lengths were calculated (see below) and used to predict future and past changes in EOO, AOO and population size.

Data cleaning and preparation

Point data and ground-truthing:

Data for this study is derived from Davis *et al.*, (2012) and Moat *et al.*, (2017a). The data from Davis *et al.* (2012) was taken and then ground-truthed in Ethiopia during 15 dedicated field missions (2013–2016); four inaccurate records were removed via this process. Ground-point data collected and/or verified as wild Arabica coffee was queried from a database and used for the analyses. In total, this gave 310 unique ground-points for wild Arabica coffee (285 from Ethiopia, and 25 from South Sudan).

SDM production and preparation

For the present-day modelled distribution of Arabica coffee in Ethiopia (South Sudan was treated separately) we used the final SDM produced by Moat *et al.* (2017a), which was based on an ensemble SDM approach, with nine selected bioclimatic variables and six modelling methods (GLM, Generalized Boosted Regression Models, Generalized Additive Models, Multiple Adaptive Regression Splines (MARS), Random Forest and Maximum Entropy (Maxent)), processed using the Biomod2 R package, version 3.1–64 (Thuiller *et al.*, 2014). All 19 BIOCLIM variables (Hijmans *et al.*, 2005) were examined and reduced to nine; the nine remaining variables were significant to the model fit, not highly correlated, and represented the ecological requirements of Arabica coffee (Moat *et al.*, 2017a). The nine BIOCLIM variables used were: Annual Mean Temperature, Isothermality, Temperature Seasonality, Annual Temperature Range, Annual Precipitation, Precipitation of the

Wettest Month, Precipitation Seasonality, Precipitation of the Driest Quarter and Precipitation of the Warmest Quarter.

For the future projections we used two climate scenarios, A1B and A2, three GCMs (based on 23 GCMs examined and reviewed by Moat *et al.* (2017a, see Table 1), four date intervals (1960–1990, 2010–2039, 2040–2069 and 2070–2099), and three of the six migration scenarios devised by Moat *et al.*, (2017a). These future projections were downloaded from CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) (http://ccafs-climate.org/data_spatial_downscaling/ and http://www.ccafs-climate.org/data/). Both the original SDM and future models were at a resolution of 1 km^2; the future models were downscaled using the delta method (Ramirez-Villegas & Jarvis, 2010).

The three migration scenarios, C, D and F (Table 1) are restricted to humid forest (of the Moist Evergreen Afromontane Forest (MAF) and Transitional Rain Forest (TRF) types; classification according to Friis *et al.,* 2010), which was originally derived from Landsat data (United States Geological Survey, 2015) at a resolution of 30 × 30 m, with some manual editing to remove plantations (e.g. tea, mangoes and forestry) and other non-humid forest vegetation (Moat *et al.*, 2017a). The forest cover mask was resampled in R using the aggregate function in the package Raster (Hijmans, 2016) to give the total forest cover per 1 km^2. A typical example of these scenarios (emission, GCM and migration) is given in Figure 2.

These procedures produced a huge amount of data to process. To make this manageable, and easier to manipulate, we combined all the SDM data into one matrix, with centroids of the cells (x and y position). The raster SDMs were converted to point data using the R package 'Raster' (Hijmans, 2016). This matrix is at a resolution of 1 km^2 (using UTM zone 27 Projection) and was stored in R (R Core Team, 2016) as a data frame.

The above dataset only covered Ethiopia, but the wild species extends into a small area close to the Ethiopian border on the Boma Plateau in South Sudan (Thomas 1942; Davis *et al.*, 2006; Davis *et al.*, 2012). The specimen and ground-point data already gathered included the Boma Plateau, but the SDM matrix lacked these data. To resolve this, we imported the South Sudan SDM from Davis *et al.* (2012), into the 1960–1990 column of the matrix. Davis *et al.* (2012) show that this location is rapidly lost under climate change projections (by 2020, i.e. representing the time period 2010–2029). This projection was considered realistic on the basis of field survey (Davis *et al.* 2012): wild Arabica populations on the Boma Plateau are in poor condition, sparsely populated, some of the major canopy trees appear to have been lost through drought, and there is almost no potential for upslope migration. We also reviewed the Boma Plateau area on global forest watch (World Resources Institute, 2014) to determine the area of remaining humid forest (16.8 km^2), and this was added to the forest cover column in the matrix. The locality on Mt. Marsabit in Northern Kenya, which has been suggested as part of the wild distribution of the species is likely to be an area where Arabica has been introduced and cultivated (see review in Davis *et al.*, 2012). Mt. Marsabit is a considerable distance (500 km)

from the main populations of Arabica (Davis *et al.*, 2012) and molecular data indicates that the plants growing at this locality are associated with cultivars of Arabica coffee rather than part of the natural genetic range of the wild species (Lashermes *et al.*, 1996).

Calculation of EOO and AOO

Using the R software package (R Core Team, 2016), the matrix described above was queried for each of the four time periods (1960–1990, 2010–2039, 2040–2069 and 2070–2099), the three GCMs, the three migration scenarios, and two emission scenarios. We removed any ground-points with very low forest cover (less than 1 hectare), as these would not be viable populations, and many would be due to noise within the satellite imagery.

EOO and AOO were calculated (from cell centroids) using rCAT (Moat, 2017). In addition, we calculated EOO using just the ground-point data, and the range of possible AOO values and therefore the minimum AOO by using a moving origin and rotating grid as suggested in Moat, Bachman, Fields and Boyd 2017, in press), with 1152 iterations.

Estimating population numbers per unit area

We estimated population numbers using two models of population demographics: (1) that the population is either linearly distributed or (2) normally distributed over elevation, from high to low numbers of plants per unit area (Figure 4). We equated population numbers to the SDM suitability categories used in Moat *et al.* (2017a); Excellent, Good, Fair, Marginal and Unsuitable. These categories were derived by examining the present-day SDM values to our ground observations (ground control, absence and pseudo absences data), by comparing True Skill Statistic, Kappa, specificity vs. sensitivity and the cumulative percentage of points to give us thresholds. For the major threshold between Fair and Marginal we used a model value of 353 as a conservative balance between all the thresholds (Kappa: 504, specificity vs. sensitivity: 424, cumulative frequency 99%: 353 and TSS: 324 points). The upper categories (Excellent, Good, Fair), were chosen at equal intervals (see Figure 3 for details). Within our analysis we equate the niche classes to population demographics, i.e. under the IUCN criteria A sub-criteria b) “an index of abundance appropriate to the taxon” (IUCN Standards and Petitions Subcommittee, 2014).

It should be noted that AOO will be proportional to a constant (i.e. flat) population value. Whilst population numbers for the cultivated species are reported here, there are only a few citations for the demography of wild Arabica. According to Senbeta *et al.*, (2014) the demographic relationship for wild Arabica is a maximum of 800 coffee plants per 400 m^2 in the best areas, reducing to 40 plants per 400 m^2 in the lowest/least suitable (Figure 3). We applied a simple linear relationship, from the Excellent suitability class to zero at the edge of limits of the Fair/Marginal class boundary (Figure 2). This linear relationship is simplistic. Senbeta *et al.* (2014; fig. 2) and Moat *et al.* (2017a) show that the population follows a normal distribution. Therefore, we also mapped the niche class to this normal

distribution (Figure 4) using the mean populations from the elevation classes (Figure 3). We have used both normal and linear demographics within our analysis, where the linear represents a conservative estimate and the normal distribution closer to the actual population distribution of Arabica coffee.

The numbers presented here are similar to: farmed Arabica coffee, where plants are generally spaced around 1 m apart (Wrigley 1980); spacing distances for Ethiopian coffee cultivation (1.5–2 m between plants, and 2.5–3 m between rows (Davis *et al.*, 2018)); and plot data (16 *in situ* plots, measured by us), which show densities ranging from 1.2 to 0.04 per m^2.

Generation length

As with calculations for AOO and EOO, determination of generation length is critical when reviewing any future or past changes in population numbers, and can greatly complicate extinction risk assessments (Willis *et al.*, 2003; Fung & Waples, 2017). Estimation of generation length is difficult without full population information (Fung & Waples, 2017), which even for a well-studied species is lacking, including Arabica coffee (DaMatta *et al.*, 2007). Coffee plants are often referred to as short-lived trees (Davis *et al.*, 2018). Some population information does exist for cultivated Arabica coffee in Ethiopia (see below), but for the wild species the information is poor. For this study we reviewed the generation length for farmed Arabica coffee, for the minimum generation length, and then extrapolated to achieve generation lengths for the wild species. Our generation estimates were reviewed against available observations for wild Arabica coffee, and then used to refine our estimates (see below).

We used three methods to estimate generation length:

1. Vitality rates: defined as age of species survival and fecundity. We used the IUCN MS Excel sheet (IUCN, 2017) to calculate generation lengths, with estimates of survival rates and fecundity from expert opinion based on field survey (Davis and Moat pers. observ.).
2. Adult mortality rate: $T_d = \alpha + \frac{1}{d}$ (IUCN Standards and Petitions Subcommittee, 2016; Fung & Waples, 2017).
3. Reproductive life span model: $T_z = \alpha + z * RL$ (IUCN Standards and Petitions Subcommittee, 2016; Fung & Waples, 2017).

Where:

T_d= Generation length (years)

240 α = Age of first reproduction (years)

241 d = Adult mortality rate (years)

242 z = is a constant 'that depend[s] on survivorship and the relative fecundity of young vs. old
243 individuals in the population' (IUCN Standards and Petitions Subcommittee, 2016). We derived z
244 values by comparison with other woody plant species from (Fung & Waples, 2017)

245 RL = length of reproductive period (years)

246

247 *Generation length of cultivated Arabica coffee*

248 Cultivated Arabica coffee plants take 3–4 years to reach fruiting stage and 5–8 years to reach
249 maximum reproductive potential (Wrigley, 1988). There are on average 3,000–4,000 fruits per tree
250 (Davis *et al.*, 2018), although productivity drops off significantly as the coffee plant ages (e.g. to 1000
251 fruits). To rejuvenate cultivated Arabica coffee, plants are often stumped (coppiced) at an interval of
252 8–15 years, which usually brings them back to full productivity. Thus, elucidating the age of coffee
253 trees can be difficult, without the cultivation history and dendrochronology. It has been estimated that:
254 at between 7–20 years Arabica coffee trees are at their most productive, senescence is reached at
255 around 25 years, and that 40 years is the average life expectancy (Davis pers. observ.). An Arabica
256 coffee tree will fruit for around 50–60 years, but only if stumped or careful pruned. Cultivated
257 Arabica coffee trees of considerable age are reported, for example up to 140 years old (Tadesse, 2017)
258 but these have not been verified and are likely to have been stumped (coppiced).

259 Applying this to the three generation length algorithms, gives:

260 1. Vitality rates model ~ 17 years
261 2. Adult mortality model 10–24 years (d values of 0.15 to 0.5 from plants in (Fung & Waples,
262 2017))
263 3. Reproductive life span model ~ 10–16 years (z values for plants of 0.16, 0.21 and 0.33 from
264 plants in (Fung & Waples, 2017))

265 *Generation length of wild Arabica coffee*

266 We extrapolated ages from cultivated plants, but with the following modifications. It is reported that
267 wild Arabica plants in Ethiopia (Meyer, 1965) can be 20 ft (6 m) high and have a trunk diameter of 8
268 in. (20.3 cm) at ground level; and in South Sudan (Thomas 1942) 18 ft (5.5 m) high and 6 in. (20.3
269 cm) at ground level. From these records it is possible to estimate an age of 60–80 years, where 1 in. is
270 roughly equivalent to 10 years growth. It has also been widely reported (e.g. on the Internet and pers.
271 comm.) that wild Arabica coffee plants can for live up to 100 years, but this is not backed up by
272 specific citations. In the wild, Arabica coffee matures (i.e. starts to bear fruit) much later than in

cultivation, and we estimate that it will take 8–12 years for wild plants to fruit. Finally, the maximum productivity will be markedly less, probably at a maximum of around 400 fruits per tree (Davis pers. observ.), although this figure could be much higher or lower depending on specific environmental conditions (especially light levels) and the amount of competition from surrounding vegetation.

Applying this to the three generation length algorithms, gives:

1. Vitality rates model ~ 21 years
2. Adult mortality model 16–30 years (d values of 0.15 and 0.5 from plants in (Fung & Waples, 2017))
3. Reproductive life span model ~ 18–22 years (z values for plants of 0.16, 0.21 and 0.33 from plants in (Fung & Waples, 2017))

These models give a generation length of between 10–30 years, with a mean generation length of approximately 16 years for cultivated Arabica, and 21 years for wild Arabica. Estimates for generation length in other perennial plant species has been determined by (Fung & Waples, 2017), and includes 15.6 years for *Limonium delicatulum* (*Plumbaginaceae*; a pin-cushion plant), 82 years for *Grias peruviana* (Lecythidaceae; sachamangua, a small tropical tree), 169 years for a coniferous species (*Araucaria cunninghamii*. a large, temperate tree). At 21 years this is very much at the lower-end of the generation length for trees. Erring on the conservative side we have used 21 years as our generation length for reporting the metrics in this study, but we also assessed generation lengths of 16, 21 and 30 years, to see how the variation in generation length would influence the assessment of extinction risk under the IUCN Red List assessment criteria.

Future and past and future population reduction (A3 & A4)

Future populations (A3) were calculated using three generation lengths as specified by the IUCN (IUCN Standards and Petitions Subcommittee, 2016). For a generation length of 21 years and future reductions (A3), we compared 2010–2039 (2024.5) to 2010–2039 (2087.5); 2010–2039 is where we see coffee suitability peak in in Ethiopia (Moat *et al.*, 2017a). For all generation lengths we either extrapolated from the last two periods, if the three generation lengths were beyond the latest models (2070–2099), or interpolated, if between model periods. For the population analysis, each niche class area was either extrapolated or interpolated and the total population recalculated using either the linear or normal population demographics (see above). If any extrapolation gave a negative number (i.e. inferring that the niche would have died out), we defaulted this value to zero. These calculations were performed in R (R Core Team, 2016) using the 'approx' and 'lm' function, using linear fits. Future and past population reduction (A4) was calculated in a similar way, but with a baseline date of 1975 (1960–1990).

Application to the Red List criteria and ratings

We calculated all of the metrics in the statistics package R (R Core Team, 2016), using the IUCN thresholds as set out in the IUCN guidelines and criteria (Mace *et al.*, 2008; IUCN Standards and Petitions Subcommittee, 2014; Moat, 2017).

Results

Present-day geographic ranges (IUCN Criteria B)

Under IUCN criterion B, the geographic range of variables are relatively simple to measure and calculate.

B1. EOO

Using the current niche and querying only areas with forest cover of over 1 hectare, we achieved an EOO of 283,817 km^2. Additionally we calculated the EOO from the ground-point data only, in both rCAT (Moat, 2017) and GeoCAT (Bachman *et al.*, 2011; Moat *et al.*, 2017c), to check that our results were comparable. The EOO value was 107,251 km^2 in rCAT, and 107,785 km^2 in GeoCAT. This metric would fall within the Least Concern extinction risk category.

B2. AOO

Using the current niche and querying only areas with forest cover of over 1 hectare we achieved a minimum AOO of 49,440 km^2, with a mode of 49,908 km^2, maximum of 50,204 km^2 and mean of 49,874 km^2 (Figure 1). This metric would fall within the Least Concern extinction risk category. We also calculated the AOO from just the ground-point data in both rCAT (Moat, 2017) and GeoCAT (Bachman *et al.*, 2011; Moat *et al.*, 2017c): the EOO was 512 km^2 in rCAT and 508 km^2 in GeoCAT. We would not expect these AOO values to be accurate as the ground-point data for Arabica coffee is hugely under-representative of population size and extent.

Present-day population size range (C, D)

Using linear demographic distribution estimates, we arrive at approximately 19.5 billion mature plants for wild Arabica over its indigenous distribution. Using the normalised demographics distribution method, the estimate is 13.5 billion mature plants. This metric would fall within the Least Concern extinction risk category.

339

340 ### Number of locations

341 For the number of locations we used the IUCN definition of location: 'a geographically or
342 ecologically distinct area in which a single event will affect all individuals' (IUCN, 2012). For wild
343 and cultivated Arabica coffee, climate is the main driver for the distribution of the species (Moat *et*
344 *al.*, 2017a). The locations covered by the natural distribution of wild Arabica represent different
345 climate regimes (Davis *et al.*, 2018; Moat *et al.*, 2017a), which will affect the species differently
346 under a changing climate. Within Ethiopia there is a major climatic division, east and west of the
347 Great Rift Valley, as discussed in (Moat *et al.*, 2017a), giving two locations for wild Arabica coffee.
348 A third would be the Boma Plateau in South Sudan, although this location is projected to fall out of
349 climatic suitability by 2020, representing the time period 2010–2029 (Davis *et al.*, 2012). There is a
350 fourth locality in the north, on the Zege Peninsula (Bahir Dar), located at the southern edge of Lake
351 Tana. Niche models indicate that the Zege Peninsula is potentially part of the wild distribution of
352 Arabica coffee, and forest coffee is cultivated here, but it is uncertain if these are true wild Arabica
353 coffee populations, as the locals say the forest and its coffee was planted around two hundred years
354 ago. This gives three to four locations, but to invoke the number of locations criteria (based on the
355 threshold of less than five locations (IUCN, 2012) this species would need to be pushed to Critically
356 Endangered or Extinct in a very short period, and there is no evidence for this.

357

358 ### Population size reduction (IUCN Criteria A)

359 On analysing future population reductions (IUCN sub criterion A3) and past to future reductions
360 (IUCN sub criterion A4), we assessed the reductions in EOO, AOO, and estimated population
361 numbers, using both the linear and normal demographic distributions (with generation lengths of 16,
362 21, 26 and 30 years. The IUCN extinction risk category under Criteria A for future projection
363 scenarios is given in Figures 5 & 6.

364

365 ## Discussion

366 Reviewing the species using present-day metrics (Criteria B: for AOO, EOO, population size and
367 number of locations), i.e. excluding climate change projections, wild Arabica coffee would be
368 assessed as Least Concern when applying IUCN Red List criteria. It is only when applying climate
369 change to the past to future and future to future changes, under Criteria A, that we see the species fall
370 within the higher-level IUCN extinction threat categories. The difference between these two sets of
371 analyses is profound.

We limit most of our discussion below using a generation length of 21 years (Figure 5, see table in top right of figure) but will also comment on the influence of different generation length estimates on the final extinction assessment.

Migration scenarios

Our three migration scenarios (Table 1) are taken from (Moat *et al.*, 2017a). Migration scenario C allows the species to move anywhere within the present-day forest cover, and we have preserved this scenario for the analysis. However, we think it is unrealistic, due to the following points. (1) The assumption is that the new niche space will have no competition (i.e. that Arabica coffee can readily occupy the new niche), which is unrealistic. (2) If wild Arabica could move into these new niches, in some cases it will need to move hundreds of kilometres from the main population; the probability of the species moving to this space in a short period of time is unrealistic (Davis *et al.*, 2012). (3) The time periods given here for the three generation lengths, would only allow a very short period for: random distributions to a new site, establishment, and breeding. (4) The new niches are often on the lowest part of the niche suitability for Arabica coffee, and so the species will not have optimal conditions to establish and reproduce. (5) That the niche would have the correct soils and microclimate (i.e. humid forest or the correct type and structure). Nonetheless, migration scenario C does serve some purpose, and particularly what could be achieved with intervention (i.e. assisted migration for conservation purposes, including the movement of propagules and establishment of suitable growing conditions, i.e. humid forest). Even with migration scenario C (which represents a best-case scenario) we can see than the species would receive an IUCN risk category of Endangered, using the normally distributed population demographic model and future reductions (IUCN sub criterion A3). This is due to the dramatic reduction (and in some cases loss) in the most suitable niches for Arabica coffee (the 'Excellent' niche (Moat *et al.*, 2017a)) for areas by the end of the century (Moat *et al.*, 2017a).

The other two migration scenarios (D and F), either restrict wild Arabica coffee to its current (1960–1990) niche (migration scenario D) or restrict the species to all previous niches (migration scenario F), i.e. the niche cannot drop below the threshold during any previous period. For the D and F migration scenarios the IUCN risk categories would be (for 21 years): D = CR (2 metrics), EN (9 metrics), and VU (13 metrics); and for F = CR (3 metrics), EN (9 metrics), and VU (17 metrics). Details are given in Figure 5. There is little difference between the results for these two migration scenarios; there is an average 2% difference, with migration scenario F showing the highest reductions.

Emission scenarios

There was considerable variability for the two emission scenarios A2 and A1B, with a -30% to +30% difference in reduction/increase in the niche, between the two. Much of this variation was in EOO,

which is not surprising as the EOO metric can be highly variable and sensitive to outlying occurrences (Keith *et al.*, 2000, 2018; Hartley & Kunin, 2003). The future projections (IUCN sub criterion A3), with emission scenario A2, consistently reports higher loses in AOO and the two population metrics, as expected.

General circulation models (GCMs)

We used three GCMs for the future projections under climate change, which provided representative coverage of the variability in climate modelling, without having to process all available (23 or more) GCMs (Moat *et al.*, 2017a). The variability between GCM reductions was not large, and generally below 10%.

Past to future vs. future reductions (sub criteria A3 and A4)

Predictably, there is a considerable difference between these two metrics, mainly due to the coffee niche coming into its best condition in 2010–2039 (Moat *et al.*, 2017a). This is because A4 (past and future) is always reporting less reduction than A3 (future).

Reduction metrics

The AOO metrics, and population numbers with linear demographics and normal demographics, behave consistently. Due to its geometric characteristics, EOO can change dramatically, with substantial changes in the area it reports, due to the loss and gains of outlying areas (Keith *et al.*, 2000, 2018; Hartley & Kunin, 2003). The inclusion (and its loss under future projections) of the uncertain population from the Zege Peninsula (near Bahir Dar, the most northly population in Figure 2), will be driving much of the change in the EOO. On this basis we would advise caution with interpretation of the EOO changes (Figure 5), and we do not use it in our final extinction risk assessment. Nonetheless, the two models for population demographics show the greatest change, with the results from the normal distribution population model showing the most dramatic reductions, which is due to the rapid loss of the Excellent niche category (Moat *et al.* 2017a) as this century progresses (towards 2099). The linear population model shows the same trend, but with less dramatic changes as the century progresses. Regardless, both show an IUCN extinction risk assessment of Endangered for a generation length of 21 years.

Generation length

Based on field observations and published information we estimated a generation length of 16–30 years, with 21 years probably representing a conservative value for the generation length of wild Arabica coffee. A summary of the percentage reductions for different generation lengths is shown in Figure 6. The results for 30 years should be viewed tentatively, as we are projecting far beyond our last time-period (2070–2099 vs. 2115, which is over 30 years of extrapolation). Even at 16 years, six of the metrics point to Endangered. With our conservative generation length estimate of 21 years, 23

of our metrics point to Endangered and a few (four) point towards the higher category of Critically Endangered. Overall, there is a skew towards higher IUCN extinction risk categories as the generation length increases (Figure 6).

In the context of deforestation

Up until this point we have not considered deforestation for the IUCN extinction risk assessment and have assumed forest cover to be static. However, historical deforestation levels in Ethiopia have been dramatically high and are ongoing (Reusing, 2000; World Resources Institute, 2014), as detailed below. Comparing different deforestation studies is difficult, as they use various definitions and classifications for forest types. The original/potential (i.e. without or before the intervention of humankind) extent of forest cover has been given by EFAP, (1994) and Friis et al., (2010), as 340,000 km^2 and 280,470 km^2, respectively. Although these studies use different classifications and scales, they do give an indication that the original forest cover of Ethiopia is in the region of 25–31% of Ethiopia's total land surface area. There is no universal agreement on the remaining forest cover (Wakjira et al., 2008), but the majority of studies agree that present-day forest cover is around 4% of the total land surface area of Ethiopia (Reusing, 1998, 2000; Wakjira et al., 2008).

On reviewing studies from (Reusing, 1998, 2000; Wakjira et al., 2008; World Resources Institute, 2014), we can report that the rates of forest loss (Reusing, 1998, 2000) shows reductions of 54% and 61% over 23 and 25 years (from 1971–1975 to 1996–1997 and 1973–1999), respectively, for natural, humid (Afromontane) forest. These values are backed up by (Wakjira et al., 2008), who looked in detail at a smaller area of humid coffee forest in south western Ethiopia, and showed that between 1973–2005, 32% of the forest cover had been lost, and in some areas there has been a 50% loss in a 32 year period alone. The majority (70%) of the reduction was due to smallholder expansion and forest conversion to agroforestry systems (Wakjira et al., 2008). Finally, forest reduction is still continuing to the present day: between 2001–2013 there was a reduction in tree cover of 2,260 km^2, with very little (only 630 km^2) afforestation (Hansen et al., 2013; World Resources Institute, 2014). It should, however, be noted that all the above metrics cover many forest types in Ethiopia and that the main deforested areas are in the South East and South West (Moat et al., 2017b). It would be very difficult to simply equate and extrapolate these tree-cover loss figures to just

the humid forests where wild Arabica coffee occurs; additionally, we would also need to either extrapolate into the future or the past to cover the 63 years (three times generation length) needed. Nonetheless, we would suspect that the reduction figures will be high and possibly comparable to the figures for future reductions from climate change. We have not used the deforestation figures given above in an Arabica extinction risk assessment, due to the uncertainty in forest definitions amongst the various studies and the lack of data over the time period needed, but we suggest that this could be rectified with a dedicated study of the temporal changes in suitable humid forest (Moist Evergreen Afromontane Forest (MAF) and Transitional Forest (TRF) types; Friis et al., 2010) across the region, using remote sensing.

CMIP3 versus CMIP5

The projections used here are based on the WCRP CMIP3 (Meehl GA et al., 2007) multi-model datasets (Moat et al., 2017a). The newer and more developed WCRP CMIP5 multi-model ensemble (Taylor et al., 2012) has become available as downscaled datasets (at 1 km^2 resolution). Knutti & Sedláček (2012) compared CMIP5 and CMIP3 and stated: "The spatial patterns of temperature and precipitation change are also very consistent. Interestingly, the local model spread has not changed much despite substantial model development and a massive increase in computational capacity". A direct comparison between CMIP3 and CMIP5 is not straightforward, as CMIP3 uses emission scenarios, whereas CMIP5 uses RCPs (Knutti & Sedláček, 2012). However, Moat et al. (2017a) and Knutti & Sedláček (2012) have compared RCP8.5 with the A2 emission scenario, and report that within Ethiopia the only substantial difference observed was a 0.9 °C increase in temperature, but with an increase in the derivation between GCMs, and a small increase in rainfall (in the North and Eastern areas), but again with increasing displacement between GCMs. The increase in temperature observed for RCP8.5 (i.e. 0.9 °C) would indicate that both the A2 and A1B scenarios could be more conservative, compared to RCP8.5; the small increase in rainfall (up to 130 mm per annum, but with very high variability between GCMs) would not be enough to negate the

497 change in temperature (Moat et al., 2017a). If temperature change were to follow RCP8.5 (CMIP5),
498 we would see an intensification of the negative changes shown here using CMIP3.

499
500

501 ## Closing remarks

502 We have shown that climate change could alter the climatic suitability of wild Arabica coffee
503 populations in Ethiopia and South Sudan, resulting in a projected decline in EOO, AOO, and more
504 substantial reductions in population numbers (more than 50% reduction). If we were to apply the
505 precautionary rule (the worstcase scenario) this would give coffee the extinction risk value of
506 Critically Endangered (10% of the results, for a generation length of 21 years, IUCN criteria A3 and
507 migration scenarios D and F; Figure 5), but we feel that the assessment of Endangered is more
508 justifiable (50% of the results, for a generation length of 21 years, IUCN criteria A3 and migration
509 scenarios D and F; Figure 5). An IUCN extinction risk assessment for Wild Arabica coffee lacking the
510 inclusion of climate change projections would result in the extinction risk category of Least Concern;
511 applying climate change projections as part of the IUCN Red List criteria methodology results in an
512 assessment of Endangered, under IUCN Criterion A (sub-criteria A3b), which is three categories
513 above Least Concern. The full IUCN extinction risk assessment for Arabica coffee is: Endangered,
514 with population reductions projected to be greater than 70% within a 63-year window (2025–2088),
515 based on a generation length of 21 years and using an index of population abundance (EN A3b).

516 Generation length is critical when applying the IUCN criteria. Here we have erred here on the
517 side of caution by using a generation length of 21 years, but if it can be demonstrated that Arabica
518 coffee has a longer generation length (and 26 years would be sufficient) there is a possibility that the
519 species will be pushed into the extinction risk category of Critically Endangered. We have assumed
520 that forest levels are static, but it is clear that there is a backdrop of rapid and continuing deforestation
521 in Ethiopia and South Sudan. If deforestation metrics were included into the IUCN extinction risk
522 assessment, the outcomes are likely to be even more negative (i.e. climate change plus deforestation),
523 and if deforestation were to remain high and consistent it could impose a stronger driver of extinction

risk than climate change alone, at least in short-term. Some locations, such as the Boma Plateau (South Sudan) and wild arabica coffee locations on the eastern side of the Great Rift Valley in Ethiopia (and especially the Bale (Harenna) forest area) are rapidly lost according to climate change projections, a result that receives unanimous agreement across a range of GCMs (Davis *et al.* 2012; Moat *et al.* 2017a, b). In Ethiopia and South Sudan both of these areas coincide with high and ongoing rates of deforestation, indicating that there would be a substantial negative compounding influence (i.e. deforestation and climate change). Germplasm from the Boma Plateau (South Sudan) and Bale (Harenna) forest area is thus a high priority for *ex situ* conservation, and possibly (*in situ*) assisted migration. The area of coffee forest presently contained within protected areas is small (1,681 km^2; about 4% of the existing wild coffee forest area) and in the future some of these protected areas will need to incorporate higher elevation to ensure the species continued protection at these sites (Davis *et al.*, 2012; Moat *et al.*, 2017a).

The results reported in this paper, shows that intervention could make a substantial difference to the future of wild Arabica coffee. If specific activities are undertaken (particularly assisted migration, forest preservation and regeneration; see Figure 5 migration scenario C) the chances of the species becoming highly threatened (i.e. Critically Endangered) could be greatly reduced. Focused intervention actions, and especially forest preservation and re-establishment, could have a positive outcome for the species, humid forest cover, and ecosystem services, and the long-term sustainability of the Ethiopia coffee economy.

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Ethiopia) and the Ethiopian Commodity Exchange (ECX). We would also like to thank Christine Schmitt (University of Freiburg) for the use of wild coffee plot study data (for ground-point data). Additional data was gathered during the DFiD-Darwin project Mainstreaming Biodiversity Conservation and Climate Resilience at Yayu Biosphere Reserve (Ethiopia) [project 22-006], and the project Coffee and Climate Change: Climate Monitoring Across Ethiopia to Guide Evidence-based Decision Making for Farmers, financed by the Amar-Franses Foster-Jenkins Trust. We grateful acknowledge the SCIP project and other funding bodies and for financial support.

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Tables

Model/Scenario	Used in this study	Definitions
Emission scenarios	A2	A very heterogenous world with an emphasis on family values and local traditions, A2 reaching 29.1 giga tonnes of carbon (GtC)
	A1B	Rapid economic growth followed by rapid introductions of new and more efficient technologies. A1B represents a balance across all energy sources. Reaching 13.5 (GtC) by 2099.
General Circulation models*	csiro_mk3_5	Centre for Australian Weather and Climate Research Mark, 3.5
	gfdl_cm2_1	Geophysical Fluid Dynamics Laboratory, Coupled Climate Model 2.1
	bccr_bcm2_0	Bjerknes Centre for Climate Research, Bergen Climate Model, Version 2
Migration scenarios (Moat *et al.*, 2017a)	C	Plants can only grow within suitable forest cover, within any suitable niche (i.e. can move within suitable forest).
	D	No Migration. Plants can only grow within suitable forest cover and only in known suitable niche (restricted to present-day forest cover and suitable niche).
	F	Plants can only grow within suitable forest cover and suitable niche, but only if niche does not drop outside of suitability during any 30-year time-period.
Population size reduction (IUCN Standards and Petitions Subcommittee, 2016)	A3	Population reduction projected, inferred or suspected to be met in the future (up to a maximum of 100 years).
	A4	An observed, estimated, inferred, projected or suspected population reduction where the time-period must include both the past and the future (up to a max. of 100 years in future), and where the causes of reduction may not have ceased OR may not be understood OR may not be reversible.

*Table 1. Models and scenarios used within this study. *Note. Three out of the 23 GCMs reviewed by Moat et al. (2017a).*

Figure Captions

Figure 1. Map of potential wild Arabica coffee in Ethiopia and South Sudan. Green areas represent the coverage of the humid forest types where wild Arabica coffee could occur (where there is ≥ 1% of forest cover in each km^2). Map generated from species distribution models (SDMs) and remote sensing (Davis et al. 2012 [one SDM]; Moat et al. 2017a [SDMs and remote sensing]). *Humid forest represented by Moist Evergreen Afromontane Forest (MAF) and Transitional Rain Forest (TRF) types (Friis et al., 2010). Agroforestry systems in Sidama (south of Awassa) are no longer wild habitats but may contain wild type plants originating from this area. Other forest areas may be highly modified compared to primary forest areas.*

Figure 2.Maps and metrics for one example future projection; emission scenario A1b, GCM gfdl_cm2_1 and migration scenario D (see Table 1) showing SDMs and figures for AOO, EOO and population numbers, for 1960–1990, 2010–2039, 2040–2069 and 2070–2099. The record from Bahir Dar (in the far north, for the time periods 1960–1990 and 2010–2039) is included here, although it is uncertain whether this represents an indigenous population (Davis et al., 2018).

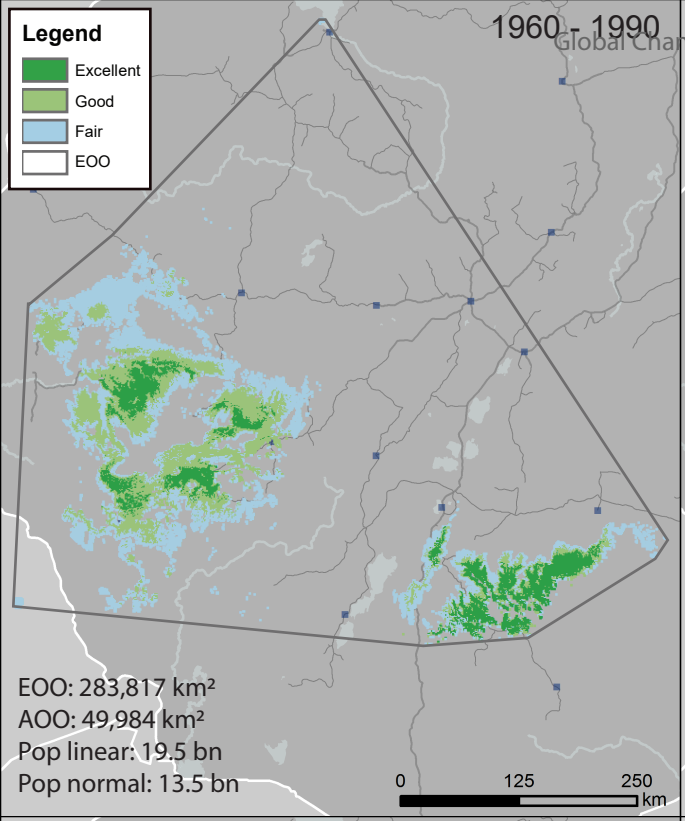
Figure 3 Graphs of five threshold statistics vs. model values (Moat et al., 2017a). Threshold values and statistics used for SDM classification. Y value = threshold statistic value, X = SDM model value (from 0 unsuitable to 1000 excellent). Actual categories used for cut-offs are highlighted with vertical black lines. Threshold metrics for categorising model suitability (statistic type with maximum model threshold values given in parentheses): Kappa (504); True skills statistic TSS (324); Sensitivity=Specificity (424); accumulative percentage of ground observation points 100% (177); 99% (353); 95% (462); 90% (552); 65% (737); 50% (764); 35% (780); 25% (792); 10% (840); 5% (904); 1% (914).

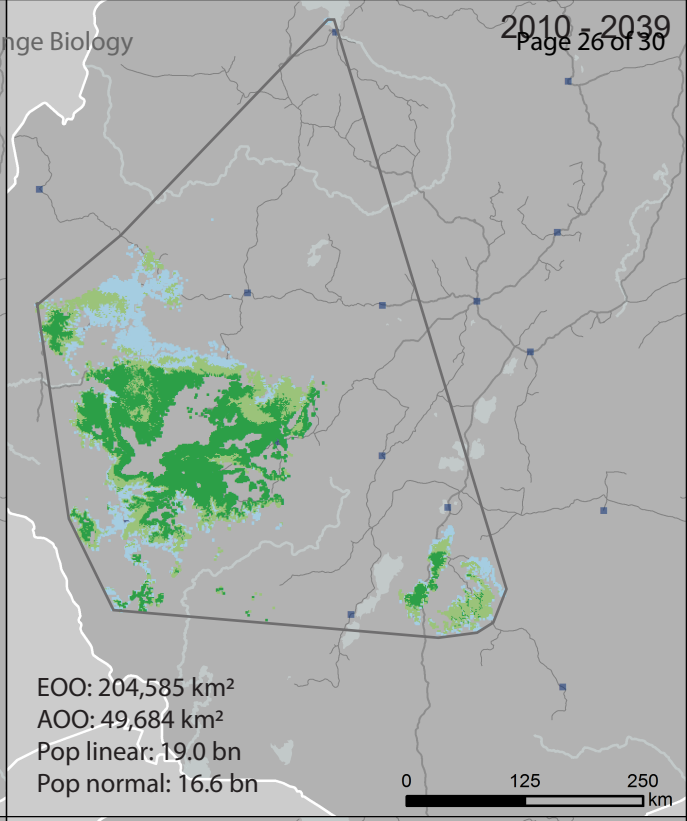
Figure 4. Histogram of wild coffee abundance (per 20 ×20m plot) vs. elevation (adapted from Senbeta *et al.*, 2014) *and niche classes used in this analysis. Blue squares represent values used for simple linear population demographics, red circles for values of the mean of the elevation classes for each suitability class and equal to the normal distribution.*

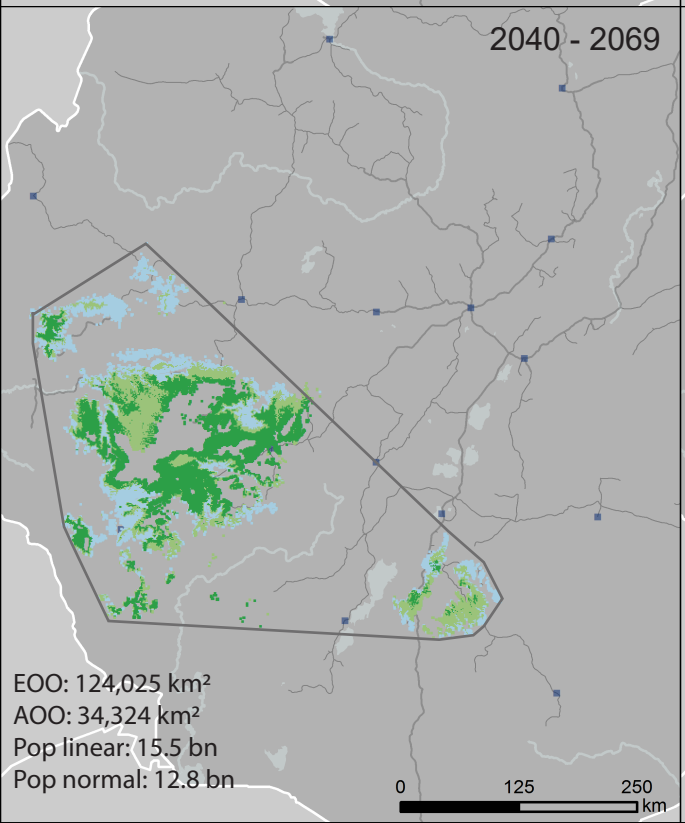
Figure 5. Rates of reduction (percentage) using generation lengths of 16, 21, 26 and 30 years. Green = Least concern (LC), Yellow = Vulnerable (VU), Orange = Endangered (EN), Red = Critically Endangered (CR). Migration scenario C is shown in grey figures as these percentages will only be achieved with considerable intervention (e.g. assisted migration, with replanting of forest). N.B. We would advise caution with the interpation of changes in EOO due to the inclusion of an outlining occurrence in the north (Zege Peninsula, near Bahir Dar) (Figure 2).

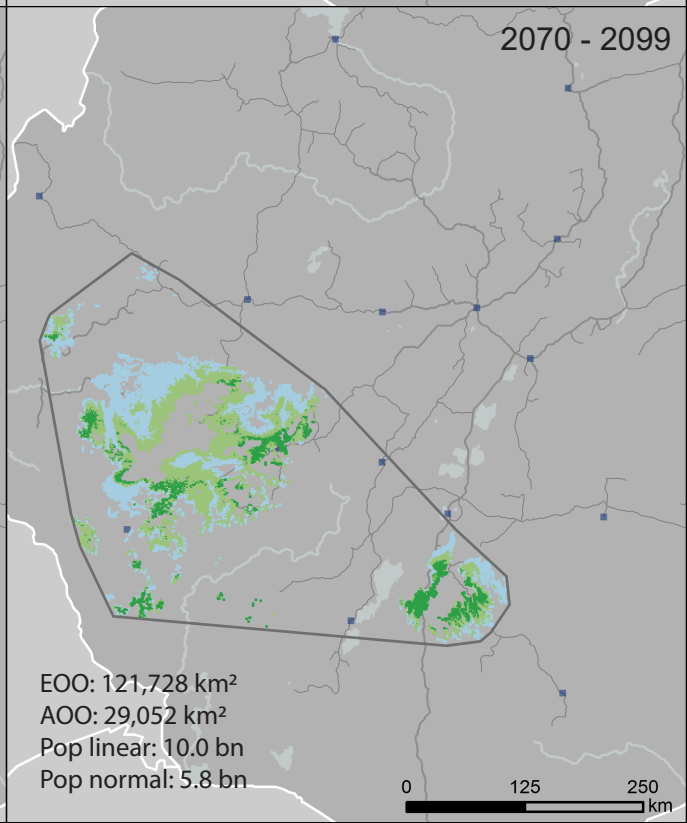
Figure 6. Histograms of percentage reduction (AOO, EOO and population measures), with differing generation lengths. X = percentage change in metric (IUCN thresholds as shown LC = Least Concern, VU = Vulnerable, , CR = Critically Endangered. Y = number of measures in the percentage change class.

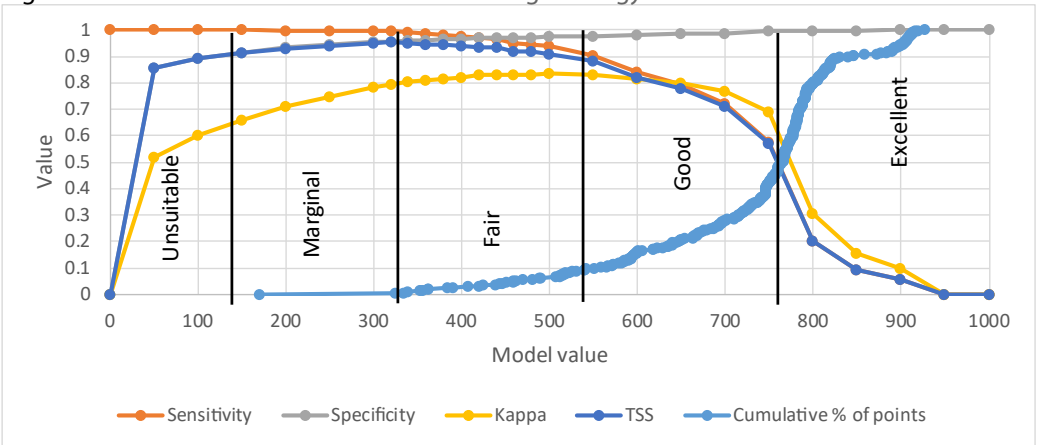

Shire (Inda Silase)
Mekele
SUDAN
Gondar
Asayita
Bahir Dar
Dese
ETHIOPIA
Asosa
Debre Birhan
Dire Dawa
Harar
Nekemte
Ambo
Addis Ababa
Asbe Teferi
Adama
Jimma
Hosaina
Hawassa
Goba
Mizan Teferi
Arba Minch
SOUTH SUDAN
Negele
KENYA
0
120
240
km

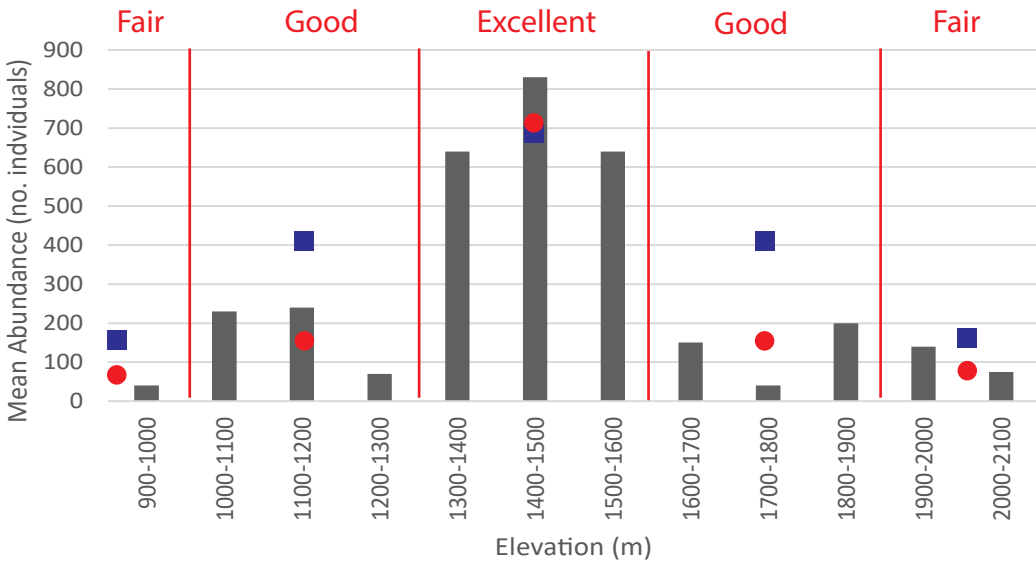

Legend
Excellent
Good
Fair
EOO
1960 - 1990
EOO: 283,817 km²
AOO: 49,984 km²
Pop linear: 19.5 bn
Pop normal: 13.5 bn
0
125
250
km


2010 - 2039
EOO: 204,585 km²
AOO: 49,684 km²
Pop linear: 19.0 bn
Pop normal: 16.6 bn
0
125
250
km


2040 - 2069
EOO: 124,025 km²
AOO: 34,324 km²
Pop linear: 15.5 bn
Pop normal: 12.8 bn
0
125
250
km


2070 - 2099
EOO: 121,728 km²
AOO: 29,052 km²
Pop linear: 10.0 bn
Pop normal: 5.8 bn
0
125
250
km


Value
Model value
Unsuitable
Marginal
Fair
Good
Excellent
Sensitivity
Specificity
Kappa
TSS
Cumulative % of points


Fair
Good
Excellent
Good
Fair
Mean Abundance (no. individuals)
900
800
700
600
500
400
300
200
100
0
900-1000
1000-1100
1100-1200
1200-1300
1300-1400
1400-1500
1500-1600
1600-1700
1700-1800
1800-1900
1900-2000
2000-2100
Elevation (m)

Generation length = 16 years

Migration scenario	Emmision senario	GCM	A3 EOO	A3 AOO	A3 Pop linear	A3 Pop normal	A4 EOO	A4 AOO	A4 Pop linear	A4 Pop normal
C	A2	csiro_mk3_5	-4%	24%	32%	43%	11%	-31%	-23%	-42%
C	A1b	csiro_mk3_5	-19%	16%	18%	22%	12%	-27%	-22%	-40%
C	A2	gfdl_cm2_1	-35%	20%	33%	44%	25%	-37%	-40%	-69%
C	A1b	gfdl_cm2_1	6%	20%	25%	35%	0%	-35%	-34%	-61%
C	A2	bccr_bcm2_0	-7%	21%	28%	38%	11%	-51%	-39%	-57%
C	A1b	bccr_bcm2_0	-8%	5%	10%	16%	15%	-24%	-6%	-10%
D	A2	csiro_mk3_5	34%	29%	47%	59%	29%	20%	6%	-15%
D	A1b	csiro_mk3_5	32%	25%	34%	40%	29%	20%	6%	-14%
D	A2	gfdl_cm2_1	10%	23%	46%	57%	52%	18%	-4%	-32%
D	A1b	gfdl_cm2_1	40%	22%	36%	48%	27%	19%	2%	-24%
D	A2	bccr_bcm2_0	19%	19%	32%	42%	29%	17%	-1%	-23%
D	A1b	bccr_bcm2_0	32%	18%	25%	32%	29%	20%	15%	8%
F	A2	csiro_mk3_5	36%	31%	48%	60%	29%	20%	6%	-15%
F	A1b	csiro_mk3_5	34%	28%	35%	41%	29%	20%	6%	-14%
F	A2	gfdl_cm2_1	12%	26%	47%	58%	52%	18%	-4%	-32%
F	A1b	gfdl_cm2_1	41%	25%	37%	49%	27%	19%	2%	-24%
F	A2	bccr_bcm2_0	22%	22%	34%	43%	29%	17%	-1%	-23%
F	A1b	bccr_bcm2_0	40%	20%	26%	32%	29%	20%	15%	8%
		Maximum	41%	31%	48%	60%	52%	20%	15%	8%
		Mean	30%	25%	38%	48%	34%	19%	5%	-15%

Generation length = 21 years

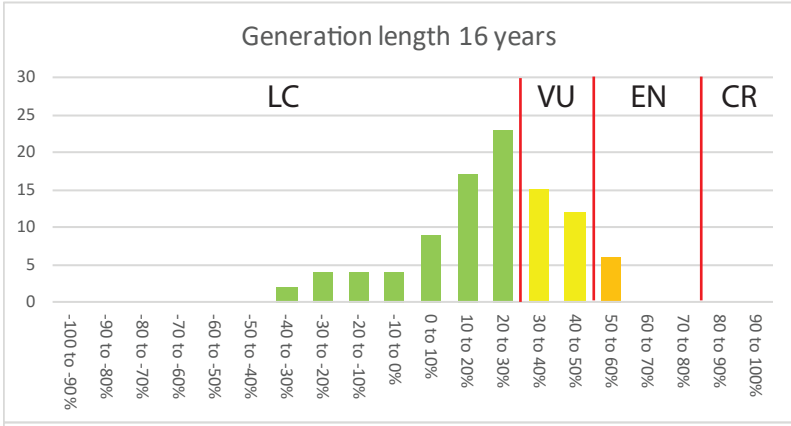
Migration scenario	Emmision senario	GCM	A3 EOO	A3 AOO	A3 Pop linear	A3 Pop normal	A4 EOO	A4 AOO	A4 Pop linear	A4 Pop normal
C	A2	csiro_mk3_5	-12%	32%	49%	64%	13%	-24%	-17%	-33%
C	A1b	csiro_mk3_5	-7%	23%	29%	34%	-1%	-22%	-20%	-36%
C	A2	gfdl_cm2_1	-42%	27%	49%	68%	17%	-30%	-33%	-59%
C	A1b	gfdl_cm2_1	-5%	23%	37%	55%	9%	-26%	-28%	-56%
C	A2	bccr_bcm2_0	-7%	26%	39%	57%	9%	-42%	-30%	-48%
C	A1b	bccr_bcm2_0	-12%	10%	25%	40%	14%	-26%	-11%	-17%
D	A2	csiro_mk3_5	33%	40%	68%	82%	41%	26%	16%	1%
D	A1b	csiro_mk3_5	32%	35%	50%	60%	40%	25%	12%	-5%
D	A2	gfdl_cm2_1	18%	35%	65%	80%	53%	22%	6%	-16%
D	A1b	gfdl_cm2_1	41%	29%	50%	69%	41%	25%	10%	-12%
D	A2	bccr_bcm2_0	35%	27%	48%	65%	29%	20%	5%	-15%
D	A1b	bccr_bcm2_0	32%	28%	42%	55%	40%	23%	18%	10%
F	A2	csiro_mk3_5	37%	43%	69%	83%	41%	27%	16%	1%
F	A1b	csiro_mk3_5	35%	37%	51%	61%	40%	26%	12%	-5%
F	A2	gfdl_cm2_1	21%	38%	67%	81%	53%	23%	6%	-15%
F	A1b	gfdl_cm2_1	42%	33%	52%	71%	41%	25%	10%	-11%
F	A2	bccr_bcm2_0	38%	33%	51%	66%	30%	21%	6%	-15%
F	A1b	bccr_bcm2_0	41%	31%	44%	57%	42%	23%	18%	10%
		Maximum	42%	43%	69%	83%	53%	27%	18%	10%
		Mean	34%	35%	56%	70%	42%	24%	12%	-5%

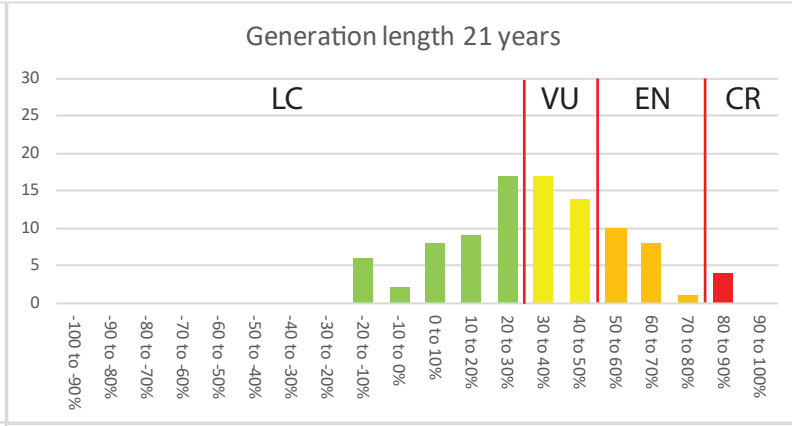
Generation length = 26 years

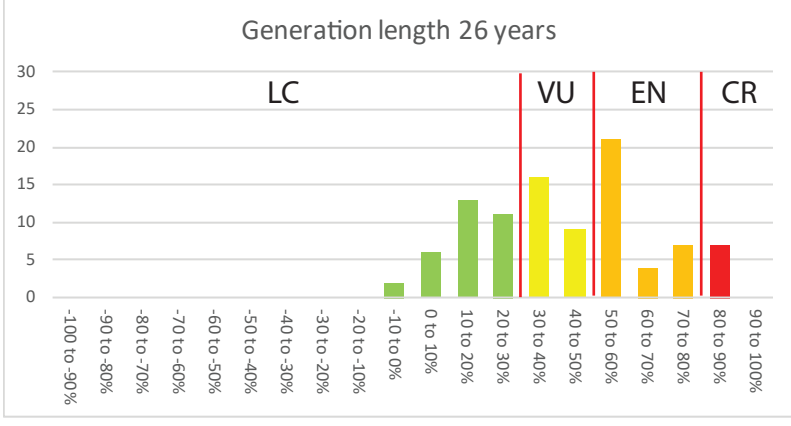
Migration scenario	Emmision senario	GCM	A3 EOO	A3 AOO	A3 Pop linear	A3 Pop normal	A4 EOO	A4 AOO	A4 Pop linear	A4 Pop normal
C	A2	csiro_mk3_5	-20%	40%	61%	79%	15%	-14%	-10%	-20%
C	A1b	csiro_mk3_5	5%	29%	40%	47%	-16%	-17%	-17%	-30%
C	A2	gfdl_cm2_1	-50%	34%	64%	78%	7%	-22%	-24%	-46%
C	A1b	gfdl_cm2_1	-17%	26%	48%	75%	19%	-15%	-21%	-47%
C	A2	bccr_bcm2_0	-6%	31%	46%	72%	6%	-30%	-19%	-35%
C	A1b	bccr_bcm2_0	-16%	16%	41%	65%	12%	-27%	-16%	-24%
D	A2	csiro_mk3_5	32%	52%	71%	84%	54%	33%	27%	18%
D	A1b	csiro_mk3_5	33%	44%	66%	79%	50%	31%	18%	4%
D	A2	gfdl_cm2_1	27%	46%	68%	85%	53%	26%	18%	4%
D	A1b	gfdl_cm2_1	41%	35%	56%	80%	55%	30%	19%	3%
D	A2	bccr_bcm2_0	51%	36%	57%	79%	29%	24%	12%	-6%
D	A1b	bccr_bcm2_0	32%	39%	58%	77%	51%	25%	20%	11%
F	A2	csiro_mk3_5	38%	55%	72%	85%	54%	33%	27%	19%
F	A1b	csiro_mk3_5	36%	46%	68%	80%	52%	33%	19%	5%
F	A2	gfdl_cm2_1	30%	50%	70%	85%	53%	27%	18%	4%
F	A1b	gfdl_cm2_1	43%	41%	58%	81%	55%	32%	20%	3%
F	A2	bccr_bcm2_0	55%	43%	60%	80%	31%	25%	13%	-6%
F	A1b	bccr_bcm2_0	41%	42%	59%	78%	56%	26%	20%	12%
		Maximum	55%	55%	72%	85%	56%	33%	27%	19%
		Mean	40%	45%	64%	81%	50%	29%	20%	7%

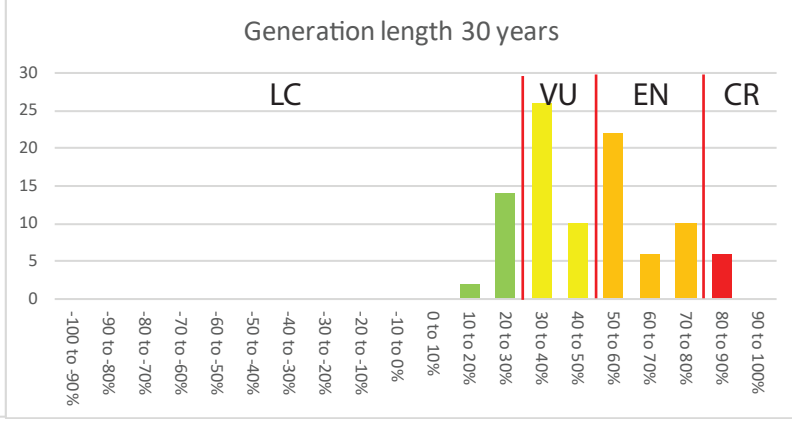
Generation length = 30 years

Migration scenario	Emmision senario	GCM	A3 EOO	A3 AOO	A3 Pop linear	A3 Pop normal	A4 EOO	A4 AOO	A4 Pop linear	A4 Pop normal
C	A2	csiro_mk3_5	-26%	47%	61%	79%	11%	-6%	5%	2%
C	A1b	csiro_mk3_5	15%	34%	49%	56%	-10%	-11%	-7%	-18%
C	A2	gfdl_cm2_1	-56%	40%	50%	76%	2%	-14%	-7%	-16%
C	A1b	gfdl_cm2_1	-26%	29%	42%	72%	12%	-11%	-9%	-23%
C	A2	bccr_bcm2_0	-6%	35%	42%	70%	6%	-24%	-7%	-13%
C	A1b	bccr_bcm2_0	-20%	21%	40%	66%	10%	-22%	-5%	-6%
D	A2	csiro_mk3_5	32%	61%	72%	84%	54%	39%	41%	39%
D	A1b	csiro_mk3_5	34%	52%	72%	85%	52%	37%	30%	21%
D	A2	gfdl_cm2_1	34%	55%	68%	84%	56%	33%	33%	27%
D	A1b	gfdl_cm2_1	42%	41%	52%	78%	57%	35%	30%	23%
D	A2	bccr_bcm2_0	64%	43%	53%	77%	37%	29%	24%	14%
D	A1b	bccr_bcm2_0	32%	48%	58%	77%	52%	31%	30%	26%
F	A2	csiro_mk3_5	38%	65%	73%	85%	55%	40%	42%	40%
F	A1b	csiro_mk3_5	37%	53%	72%	85%	53%	39%	31%	22%
F	A2	gfdl_cm2_1	38%	60%	70%	85%	56%	35%	34%	28%
F	A1b	gfdl_cm2_1	44%	47%	54%	79%	57%	37%	31%	23%
F	A2	bccr_bcm2_0	68%	51%	57%	79%	39%	31%	25%	15%
F	A1b	bccr_bcm2_0	42%	50%	59%	78%	58%	32%	31%	27%
		Maximum	68%	65%	73%	85%	58%	40%	42%	40%
		Mean	44%	53%	64%	82%	53%	35%	33%	27%


Generation length 16 years
LC
VU
EN
CR
30
25
20
15
10
5
0
-100 to -90%
-90 to -80%
-80 to -70%
-70 to -60%
-60 to -50%
-50 to -40%
-40 to -30%
-30 to -20%
-20 to -10%
-10 to 0%
0 to 10%
10 to 20%
20 to 30%
30 to 40%
40 to 50%
50 to 60%
60 to 70%
70 to 80%
80 to 90%
90 to 100%


Generation length 21 years
LC
VU
EN
CR
30
25
20
15
10
5
0
-100 to -90%
-90 to -80%
-80 to -70%
-70 to -60%
-60 to -50%
-50 to -40%
-40 to -30%
-30 to -20%
-20 to -10%
-10 to 0%
0 to 10%
10 to 20%
20 to 30%
30 to 40%
40 to 50%
50 to 60%
60 to 70%
70 to 80%
80 to 90%
90 to 100%


Generation length 26 years
LC
VU
EN
CR
30
25
20
15
10
5
0
-100 to -90%
-90 to -80%
-80 to -70%
-70 to -60%
-60 to -50%
-50 to -40%
-40 to -30%
-30 to -20%
-20 to -10%
-10 to 0%
0 to 10%
10 to 20%
20 to 30%
30 to 40%
40 to 50%
50 to 60%
60 to 70%
70 to 80%
80 to 90%
90 to 100%


Generation length 30 years
LC
VU
EN
CR
30
25
20
15
10
5
0
-100 to -90%
-90 to -80%
-80 to -70%
-70 to -60%
-60 to -50%
-50 to -40%
-40 to -30%
-30 to -20%
-20 to -10%
-10 to 0%
0 to 10%
10 to 20%
20 to 30%
30 to 40%
40 to 50%
50 to 60%
60 to 70%
70 to 80%
80 to 90%
90 to 100%

Paper VIII. Wild *Coffea arabica* conservation assessment: Endangered and threatened with extinction.

In submission: IUCN Red List, in preparation: Biodiversity Data Journal.

Moat, J. F., O'Sullivan R., Gole, T. W. and Davis A.P. (2017). A comprehensive species conservation assessment of Arabica Coffee (*Coffea arabica*) within a changing planet. In submission to IUCN Red List and Biodiversity Data Journal.

Status:

In submission to SIS (IUCN Species Information Service).

Author Contributions:

Conceived and designed the experiments: J.M. Performed the experiments: J.M. Analysed the data: J.M. Contributed reagents/materials/analysis tools: A.P.D., R.O. & J.M. Wrote the ms. J.M., R.O., T.W.G. & A.P.D.

Pages: 16.

Title: Wild *Coffea arabica* conservation assessment: Endangered and threatened with extinction.

Authors: Justin Moat[1,2], Tadesse Woldermariam Gole[3] and Aaron Davis[1]

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Abstract/Rational

Coffea arabica is found in North-East Tropical Africa. The largest subpopulations are in the south-west highlands of Ethiopia (west of the Great Rift Valley) and in the highlands to the east of the Great Rift Valley. A smaller additional sub-population is found in eastern South Sudan on the Boma Plateau. Its current extent of occurrence (EOO), estimated from Species Distribution Models (SDM), is 283,817 km^2 and the minimum area of occupancy (AOO) is 49,440 km^2.

Coffea arabica is widely cultivated throughout the cooler parts of the tropical belt and has become one of the world's most important commodity crop species. Much of this production is obtained from cultivated varieties that represent only a small percentage of the genetic variety, compared to that found in the wild populations of Ethiopia and South Sudan. These wild populations are highly threatened by several factors, the most salient being; deforestation, climate change, genetic erosion and pests and diseases. Deforestation due to the extraction of timber and the expansion of agricultural land, leading to habitat fragmentation, resulted in the loss of around 50% of more of the forests in south-west Ethiopia between the 1970s and 1990s, and forest losses in the humid forest habitat where wild *C. arabica* occurs continues to the present day.

Climate change is predicted to have a substantial influence on current suitable growing areas for indigenous *C. arabica* in Ethiopia and South Sudan. Future predictions using multiple general circulation models (GCMs), emission scenarios and migration scenarios, show that the population is likely to reduce by over 50% (and even a few predict over 80%) by 2088. In addition to population, EOO and AOO is also shown to reduce by over 30%. Furthermore, present day models compared to the near future (2038), show reduction of EOO of over 40% (with some over 50%). This is using a conservative estimate of generation length of 21 years.

This future reductions due to climatic suitability change, will affect the species growing area and populations, resulting in an projects decline population of over 70% in 50% of the emission scenarios and migration scenarios. This warrants a rating Endangered, with population reductions projected to be greater than 70% within a 63-year window (2025–2088), based on a generation length of 21 years and using an index of population abundance (EN A3b).

Keywords

Endangered, Climate change, habitat loss, Ethiopia, South Sudan, extinction

Coffea arabica L.

Species information

Common names

Common name	Language	Primary
Arabica coffee	English	yes
Coffee Arabica	English	
Coffee	English	
Arabian Coffee	English	

Taxonomy

Kingdom	Phylum	Class	Order	Family
Plantae	Spermatophyta	Magnoliopsida	Rubiales	Rubiaceae

Taxonomic notes

Source: (Davis AP *et al.*, 2006) Davis, A.P., Govaerts, R., Bridson, D.M. and Stoffelen, P. 2006. An annotated taxonomic conspectus of the genus Coffea (Rubiaceae). Botanical Journal of the Linnean Society 152: 465-512.

Region for assessment

- North Eastern Africa
- Global

Geographic range:

Range description:

Coffea arabica is found in North-East Tropical Africa. The largest subpopulations are in the south-west highlands of Ethiopia, to the west of the Great Rift Valley, which is the centre of diversity for the species (Labouisse J-P *et al.*, 2008). A smaller additional subpopulation is found in eastern South Sudan in the Boma Plateau (Thomas, 1942, Davis *et al.*, 2006, 2012). Mt. Marsabit in northern Kenya has been suggested as a locality for wild *C. Arabica*, although DNA studies indicate that the population falls within the range of introduced Arabica cultivars (Lashermes P *et al.*, 1996). Moreover, Mt. Marsabit is at least 500 km from the main population in Ethiopia (Davis *et al.*, 2012). Re-identification of herbarium specimen from the Imatong Mts. in southern South Sudan, has shown that it is wild *C. canephora* (robusta coffee) rather than wild *C. arabica*.

Biogeographic realm:

- Afrotropical

Countries:

- Ethiopia: Extant: Native
- South Sudan: Extant: Native
- Kenya: Extant: Introduced
- Uganda: Extant: Introduced
- Tanzania: Extant: Introduced
- Gabon: Extant: Introduced
- Republic of Congo: Extant: Introduced
- Democratic Republic of Congo: Extant: Introduced
- Cameroon: Extant: Introduced
- Malawi: Extant: Introduced
- Madagascar: Extant: Introduced
- India: Extant: Introduced
- Bangladesh: Extant: Introduced
- Thailand: Extant: Introduced
- Vietnam: Extant: Introduced
- Cambodia: Extant: Introduced
- Indonesia: Extant: Introduced

- Philippines: Extant: Introduced
- Papua New Guinea: Extant: Introduced
- Mexico: Extant: Introduced
- Cuba: Extant: Introduced
- Dominican Republic: Extant: Introduced
- Puerto Rico: Extant: Introduced
- Guatemala: Extant: Introduced
- Honduras: Extant: Introduced
- Nicaragua: Extant: Introduced
- Costa Rica: Extant: Introduced
- Panama: Extant: Introduced
- Colombia: Extant: Introduced
- Venezuela: Extant: Introduced
- Ecuador: Extant: Introduced
- Brazil: Extant: Introduced
- Peru: Extant: Introduced
- Bolivia: Extant: Introduced
- Paraguay: Extant: Introduced

Map

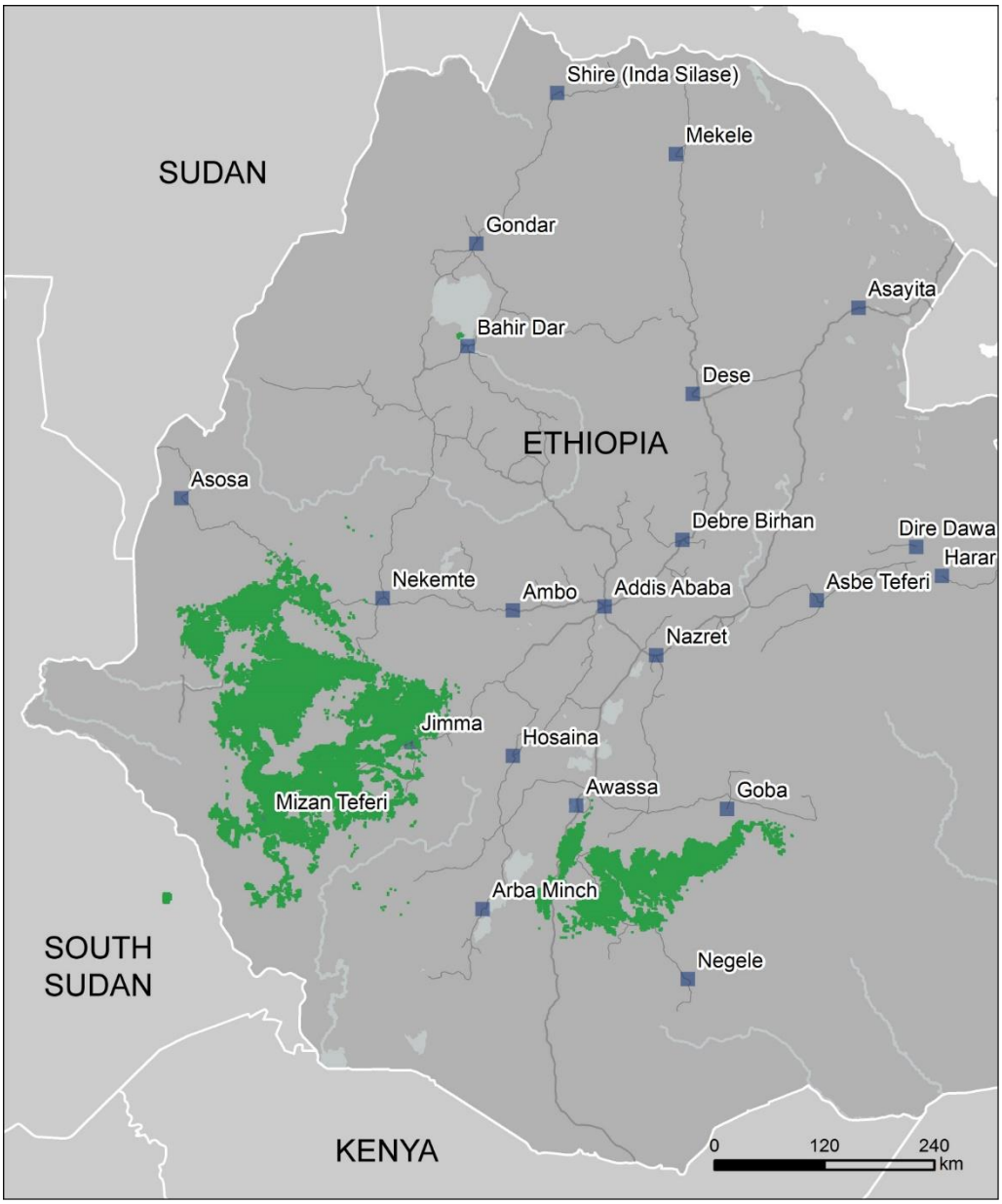


Figure 1. Map of potential wild Coffea arabica in Ethiopia and South Sudan. Green areas represent the humid forest type where wild C. arabica occurs, or may have occurred in pre-agricultural times (forest represented is ≥ 1% forest in each km²).

Basis of EOO and AOO:

Observed

Extent of occurrence:

283,817 km²; Declining (inferred), (c) a decline in area of occupancy, extent of occurrence and/or quality of habitat

Area of Occupancy:

49,440 km^2; Declining (inferred), (c) a decline in area of occupancy, extent of occurrence and/or quality of habitat

AOO narrative:

Minimum area of occupancy (AOO) 49,440 km^2 with a mode value of 49,908 km^2, maximum of 50,204 km^2 and mean of 49,874 km^2 using 2 x 2 km cells with multiple origins and rotation for the grid following (J. Moat, Bachman, R. Field and Boyd 2018), using 1024 iterations.

Severely fragmented: No; **Min Elevation/Depth (m):** 950 **Max Elevation/Depth (m):** 1950

Population:

Declining (inferred), (c) a decline in area of occupancy, extent of occurrence and/or quality of habitat

Population notes:

Due to its large size, the exact population size of indigenous *C. arabica* is unknown but the species is widespread in south and south western Ethiopia, with a smaller population in eastern South Sudan (restricted to a small area on the Boma Plateau). Estimate from SDMs and density data from (Senbeta *et al.*, 2014), suggest the current population is in the range of 13.5–19.5-billion mature plants (Moat *el al* 2018, in press).

The population is inferred to be in decline due to losses of its natural habitat and predicted to decline in the future due to climate change (Davis *et al.*, 2012; Paper VII, *Moat et al.* 2018 in press). Between the 1970s and 1997 52% of the natural coffee habitat in south-west Ethiopia was lost (Gole *et al.*, 2003). An analysis of Landsat images from 1973, 1987, 2001 and 2005 covering Afromontane forest in southwestern Ethiopia revealed a reduction of up to 50% in forest cover in some areas between 1973 and 2005 (Tadesse *et al.*, 2008).

Population trend: Decreasing; **Population size:** 13,500,000,000 – 19,000,000,000;

All individuals in one sub population: No; **Extreme fluctuations:** No

Habitats and ecology

Habitat notes:

Coffea arabica is found in cool humid, evergreen forest as an understory tree or shrub (Davis *et al.*, 2012, 2017). Climatically, it is a plant of subtropical, almost temperate regions, which do not suffer frost or strong winds, a well distributed rainfall and a defined dry season lasting 4–5 months. *Coffea arabica* prefers a deep, well-drained, loamy soil, which is slightly acidic (pH 5.8–6.0 being the optimum for good root growth) and rich in humus and exchangeable bases. Soil moisture and oxygen are required throughout the rooting depth. The optimum mean temperature range for *C. arabica* is 18-23°C. Temperatures above 30°C are detrimental to growth (Coste, 1992).

Biogeographic Realms: 1.5 Subtropical/Tropical Dry Forest & Subtropical/Tropical Moist Montane Forest; **Habit:** Tree/Shrub; **System:** Terrestrial

Threats

Threats notes:

Deforestation, climate change, genetic erosion and diseases and pests are the major threats to this species. *Coffea arabica* has its primary centre of diversity in the south-western highlands of Ethiopia. However, this genetic diversity is under-exploited, inadequately understood, and increasingly under threat of erosion caused by a number of factors (Labouisse J-P *et al.*, 2008; Aerts *et al.*, 2012). Being an understory plant, and incapable of surviving unassisted in secondary forest, deforestation is a severe threat to wild populations of *C. arabica*. Deforestation levels in Ethiopia have been historically dramatic and are continuing to the present-day (Reusing, 2000; World Resources Institute, 2014).

From Moat *el al* (2018 in press): “Comparing different deforestation studies is difficult, as they use various definitions and classifications for forest types. The original/potential (i.e. without or before the intervention of humankind) extent of forest cover has been given by EFAP, (1994) and Friis et al., (2010), as 340,000 km2 and 280,470 km2, respectively. Although these studies use different classifications and scales, they do give an indication that the original forest cover of Ethiopia is in the region of 25–31% of Ethiopia’s total land surface area. There is no universal agreement on the remaining forest cover (Wakjira et al., 2008), but the majority of studies agree

that present-day forest cover is around 4% of the total land surface area of Ethiopia (Reusing, 1998, 2000; Wakjira et al., 2008).

On reviewing studies from (Reusing, 1998, 2000; Wakjira et al., 2008; World Resources Institute, 2014), we can report that the rates of forest loss (Reusing, 1998, 2000) shows reductions of 54% and 61% over 23 and 25 years (from 1971–1975 to 1996–1997 and 1973–1999), respectively, for natural, humid (Afromontane) forest. These values are backed up by (Wakjira et al., 2008), who looked in detail at a smaller area of humid coffee forest in south western Ethiopia, and showed that between 1973–2005, 32% of the forest cover had been lost, and in some areas there has been a 50% loss in a 32 year period alone. The majority (70%) of the reduction was due to smallholder expansion and forest conversion to agroforestry systems (Wakjira et al., 2008). Finally, forest reduction is still continuing to the present day: between 2001–2013 there was a reduction in tree cover of 2,260 km2, with very little (only 630 km2) afforestation (Hansen et al., 2013; World Resources Institute, 2014). It should, however, be noted that all the above metrics cover many forest types in Ethiopia and that the main deforested areas are in the South East and South West (Moat et al., 2017b). It would be very difficult to simply equate and extrapolate these tree-cover loss figures to just the humid forests where wild Arabica coffee occurs; additionally, we would also need to either extrapolate into the future or the past to cover the 63 years (three times generation length) needed. Nonetheless, we would suspect that the reduction figures will be high and possibly comparable to the figures for future reductions from climate change. We have not used the deforestation figures given above in an Arabica extinction risk assessment, due to the uncertainty in forest definitions amongst the various studies and the lack of data over the time period needed, but we suggest that this could be rectified with a dedicated study of the temporal changes in suitable humid forest (Moist Evergreen Afromontane Forest (MAF) and Transitional Forest (TRF) types; Friis et al., 2010) across the region, using remote sensing."

Climate change is predicted to have a substantial effect on current suitable growing areas for indigenous *C. arabica* in Ethiopia (Davis et al., 2012; J. Moat et al., 2017a, 2017b, 2018 in press). Future predictions for the species, using multiple general circulation models (GCMs), emission scenarios and migration scenarios (Moat et al. 2018, in press), show that population numbers are likely to reduce by over 50% by 2088, with the majority over 70% (and a few show over 80%). In addition to population numbers, EOO and AOO is also shown to reduce by more than 30% in many cases. Furthermore, present day models compared to the near future (2038), show reduction of EOO

of over 40% (with a few over 50%). This is using a conservation estimate of generation length of 21 years.

Furthermore, higher temperatures can be detrimental from an economic point of view. Average temperatures above 23°C can accelerate the development and ripening of fruits and leading to decreased beverage quality (Davis *et al.*, 2012; Moat *et al.*, 2017a, 2017b).

Coffee berry borer (*Hypothenemus hampei*), is the most problematic pest for coffee worldwide, and is projected to become more of a threat in East Africa as temperatures rise due to climate change (Jaramillo *et al.*, 2011). Before 2001 *H. hampei* had not been found above 1,500 m ASL, at the lower end of the natural range of *C. arabica* (1200 - 1950 m ASL), however, due to increasing temperatures it is now being found at higher altitudes, where it can infest *C. arabica* and lead to a subsequent decrease in yield (Jaramillo J *et al.*, 2009; Jaramillo *et al.*, 2011). Diseases such as coffee berry disease (CBD), caused by the *Colletotrichum kahawae* fungus, and coffee wilt disease, caused by the fungal vascular wilt pathogen *Gibberella xylarioides,* also threaten *C. arabica* in Ethiopia (Davis *et al.*, 2017).

Genetic erosion of wild populations of *C. arabica* poses a threat anywhere where cultivated and wild *C. arabica* occur in close proximity (Aerts *et al.*, 2012).

Threat	**Timing**	**Scope**	**Severity**	**Impact Score**
1.1. Residential & commercial development -> Housing & urban areas	Ongoing	-	Slow, Significant Declines	Low Impact: 4
2.1.1. Agriculture & aquaculture -> Annual & perennial non-timber crops -> Shifting agriculture	Ongoing	-	Slow, Significant Declines	Low Impact: 4
2.1.2. Agriculture & aquaculture -> Annual & perennial non-timber crops -> Small-holder farming	Ongoing	-	Slow, Significant Declines	Low Impact: 4
2.1.3. Agriculture & aquaculture -> Annual & perennial non-timber crops -> Agro-industry farming	Ongoing	-	Slow, Significant Declines	Low Impact: 4
2.2.1. Agriculture & aquaculture -> Wood & pulp plantations -> Small-holder plantations	Ongoing	-	Slow, Significant Declines	Low Impact: 4
2.2.2. Agriculture & aquaculture -> Wood & pulp plantations -> Agro-industry plantations	Ongoing	-	Slow, Significant Declines	Low Impact: 4
2.3.1. Agriculture & aquaculture -> Livestock farming & ranching -> Nomadic grazing	Ongoing	-	Slow, Significant Declines	Low Impact: 4
2.3.2. Agriculture & aquaculture -> Livestock farming & ranching -> Small-holder grazing, ranching or farming	Ongoing	-	Slow, Significant Declines	Low Impact: 4
2.3.3. Agriculture & aquaculture -> Livestock farming & ranching -> Agro-industry grazing, ranching or farming	Ongoing	-	Slow, Significant Declines	Low Impact: 4
4.1. Transportation & service corridors -> Roads & railroads	Ongoing	-	Slow, Significant Declines	Low Impact: 4

6.3. Human intrusions & disturbance -> Work & other activities	Ongoing	-	Slow, Significant Declines	Low Impact: 4
11.1. Climate change & severe weather -> Habitat shifting & alteration	Ongoing	Majority (50-90%)	Causing/Could cause fluctuations	High Impact: 8
11.2. Climate change & severe weather -> Droughts	Ongoing	Majority (50-90%)	Causing/Could cause fluctuations	Medium Impact: 7
11.3. Climate change & severe weather -> Temperature extremes	Ongoing	Majority (50-90%)	Slow, Significant Declines	Medium Impact: 7
11.4. Climate change & severe weather -> Storms & flooding	Ongoing	Majority (50-90%)	Causing/Could cause fluctuations	Medium Impact: 6

Conservation

Conservation action:

Conservation of the wild populations of *C. arabica* in eastern Africa's Afromontane forests is of fundamental importance. Being the species' centre of diversity and representing the majority of the crop species genetic diversity these wild populations provide the variability required for disease and pest resistance, climate tolerance (Davis *et al.*, 2012; Moat *et al.*, 2017a, 2017b) and new flavour profiles (Davis *et al.*, 2017). Outside Ethiopia, cultivated varieties (cultivars) are sourced from a very narrow genetic base (Anthony FM et al., 2002), and are so more susceptible to detrimental influences . To conserve this wild genetic diversity many *ex situ* genebank collections have been established, both in Ethiopia and internationally. The major ones are located in Brazil (Centro Nacional de Recursos Geneticos), Colombia (Centro Nationale de Investigaciones de Café Pedro Uribe Mejia), Costa Rica (Centro Agronomico Tropicale de Investigacion y Enseñanza), Côte d'Ivoire (ORSTOM-Institut Français de recherché scientifique pour le développement en coopération), India (Central Coffee Research Institute, Kamataka), Kenya (Coffee Research Foundation), Madagascar (Recherche Agricole a Madagascar), Tanzania (Tanzanian Agricultural Research Organization), USA (US Department of Agriculture) (Dulloo *et al.*, 1998)) and in Ethiopia at the Institute of Biodiversity Conservation and Research and the Jimma Research Station (Dubale & Tektay, 1999). Recently, five new field genebanks have been established to conserve coffee as well as medicinal plants and other forest plant species, and eight new *in situ* conservation sites are being established to conserve coffee and other agricultural species. *Ex situ* conservation of *Coffea* seeds is problematic as they display intermediate to recalcitrant seed storage behaviour and so do not survive drying (Davis AP *et al.*, 2006). Thus, long-term storage of fruit is not a viable option for ex-situ conservation at this time.

In situ conservation can both maintain the species genetic diversity whilst allowing ongoing evolutionary processes to continue as plants adapt to changing conditions (Gole *et al.*, 2003). The

Yayu Coffee Forest Biosphere Reserve in southwest Ethiopia is the largest and most important forest for the conservation of wild *C. arabica*. Since 2010 Yayu has been recognised by UNESCO as an Important Biosphere Reserve. Participatory forest management (PFM) measures are currently underway in areas such as Amora Gedel and Kontir Berhan in southwest Ethiopia to conserve wild coffee forest whilst providing sustainable livelihood benefits to local communities (a Darwin Initiative project, 2012). With deforestation being one of the major threats to wild coffee populations (Reusing, 2000; Gole *et al.*, 2003; Tadesse *et al.*, 2008) efforts to mitigate this threat are of primary importance, both to prevent further losses to the *C. arabica* genepool and for the beneficial effects the plant can have on its forest environment, which is considered to be keystone ecosystem in Ethiopia (Gole *et al.*, 2003). Shade-grown Ethiopian forest coffee has been shown to be beneficial for other species groups such as birds (Buechley *et al.*, 2015) and good management of forest coffee systems in Ethiopia has actually been shown to reduce rates of deforestation in coffee growing altitudes compared with at higher elevations, due to coffee's importance to local economies (Hylander *et al.*, 2013).

Wild populations of *C. arabica* occur in many protected areas in Ethiopia and so are afforded some degree of protection from human disturbance. However, many important and vulnerable subpopulations exist outside of protected areas and their habitats are subject to a variety of threat including, but not limited to, deforestation, fragmentation, human incursion and land use change. Some reserves, such as Yayu, require the inclusion of areas at higher elevations if they are to be successful in the longer term (Moat *et al.*, 2017b).

The Ethiopian Climate Resilient Green Economy Strategy (2011) hopes to adopt agricultural and land use practices which will have a positive impact on biodiversity including the re-establishment of forests for their economic and ecosystem service benefits (Federal Democratic Republic of Ethiopia, 2011).

Conservation in place

Action	Response
Does the Species Occur in at Least One Protected Area?	Yes, over part of range
If yes, indicate what percentage of the population is within Protected Areas (1-100%)	4.2%
Is there invasive species control or prevention?	No
Is the Taxon the Subject of any Recent Education or Awareness Programmes?	Yes

Conservation actions needed

Conservation Actions

Conservation Actions	Note
1.1. Land/water protection -> Site/area protection	-
1.2. Land/water protection -> Resource & habitat protection	-
2.1. Land/water management -> Site/area management	-
2.2. Land/water management -> Invasive/problematic species control	-
2.3. Land/water management -> Habitat & natural process restoration	-
3.1.1. Species management -> Species management -> Harvest management	-
3.1.2. Species management -> Species management -> Trade management	-
3.4.1. Species management -> Ex-situ conservation -> Captive breeding/artificial propagation	-
3.4.2. Species management -> Ex-situ conservation -> Genome resource bank	-
4.1. Education & awareness -> Formal education	-
4.2. Education & awareness -> Training	-
4.3. Education & awareness -> Awareness & communications	-

Conservation research needed

Research	Note
1.2. Research -> Population size, distribution & trends	-
1.4. Research -> Harvest, use & livelihoods	-
1.5. Research -> Threats	-
2.1. Conservation Planning -> Species Action/Recovery Plan	-
2.2. Conservation Planning -> Area-based Management Plan	-
2.3. Conservation Planning -> Harvest & Trade Management Plan	-
3.1. Monitoring -> Population trends	-
3.2. Monitoring -> Harvest level trends	-
3.3. Monitoring -> Trade trends	-
3.4. Monitoring -> Habitat trends	-

General Use and Trade Information

Wild crop relative: yes; **Use status:** yes; **CITES status:** Not listed;

Uses:

Arabica Coffee (*Coffea arabica* L.) provided 71% of the world's coffee in 2016, the remainder being derived from *C. canephora* (robusta coffee) (International Coffee Organization (ICO), 2017). Much of

this trade is from cultivated varieties which constitute a small percentage of the genetic diversity of the wild populations found in Ethiopia and South Sudan. In 2013 coffee was Ethiopia's chief source of export revenue, generating 25-30% of the country's total export earnings (Tefera & Tefera, 2014). Within its wild range, wild *C. arabica* is harvested (true forest coffee) and to a lesser degree for the pulpy parts of the fruit (beverages and foodstuffs) its leaves (which are used as a 'tea') (Davis et al., 2017) (Moat *et al.*, 2017a). The beans are also used as a source of caffeine which is used as a stimulant and a diuretic, dietary aids and in numerous pharmaceuticals.

The economic value of Ethiopia's *C. arabica* genetic benefits alone are estimated at a minimum of 0.5 to 1.5 billion US$ (Hein & Gatzweiler, 2006).

Assessment information

Date of assessment: 31/05/2017

Red list category: Endangered (EN) System: 3.1

Red list status: EN A3b

Credits

Name	Role
Justin Moat	Assessor
Robert O'Sullivan	Assessor
Tadesse Woldermariam Gole	Assessor
Aaron Davis	Assessor
Hanna Bachelor	Contributor

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397



Figure 15 Wake up and smell the coffee. Poster by the Union of Concerned Scientists.

Connecting climate change and coffee, when this was released (~2006), there was little or no evidence for the influence of climate change on coffee, and little science (at most) behind the headline.

Discussion

This thesis has demonstrated two major strands of my work in spatial analysis and plant conservation. I have applied the knowledge gained from over 25 years of research experience to predicting the response of Arabica coffee to changing climate, assessing its extinction risk, and putting in recommendations to safeguard the future of the species, both in the wild and in cultivation. The tools, methods, workflow and metrics produced during this work can be equally applied to many other species and indeed have been applied to multiple species and many regions (See Appendix II).

During the period of study, I had the unique opportunity to review the impact of the initial paper (Paper I[a]), as it is well established, in comparison to the second paper (Paper II), published in July 2017. Both papers produced a huge amount of publicity and commentary on social media, which can be tracked and at some level can demonstrate impact (see Appendix VII for an overview of the impact of these papers). I also reviewed the potential economic benefits of this coffee work and possible impact within Ethiopia (see Appendix VIII).

1. Objectives reviewed

The ultimate objective of this thesis was to forecast the fate of Arabica coffee within its homeland in a changing world, identifying the needs, methods and challenges in doing this type of analysis. Here I review each objective (see extended abstract section 5. Research objectives), highlighting the outcomes, the limitations and suggestion for future research.

1. **Understand the environmental conditions for wild and cultivated Arabica coffee in Ethiopia.** I developed the initial analysis for the environmental needs of wild coffee in manuscript I[a]. This is greatly developed in Paper II and summarised in the strategy document (Paper III) for both wild and cultivated Arabica coffee in Ethiopia.
2. **Quantify the impact of climate change on Arabica coffee in Ethiopia and identify resilience and 3. Understand cultivated and wild Arabica coffee in Ethiopia under a changing climate**. In Paper I[a], I showed that there are likely to

be negative impacts to wild coffee in Ethiopia. Although the analysis within the manuscript was limited (only one GCM, one modelling method, one migration scenario and two climate scenarios), it shows that the present coffee areas will be negatively impacted by climate change. I greatly expand on this (adding robustness and spatial confidence to the results and analysis) within Paper II and introduce different possible migration scenarios.

4. **Quantify the extinction risk and conservation status for wild Coffee in Ethiopia.** Paper VI[a] develops the code and routines to produce various conservation metrics (including AOO and EOO) from point data, quickly, and repeatably, and allowing for many iterations to be run. The specific algorithms for AOO (initially developed within Paper VI[a]) are rigorously explored and refined in Paper V. Paper VII uses these developed tools and methods, applying them to the results from Paper II to quantify the extinct risk for wild coffee and give the species a formal (IUCN) conservation assessment (Paper VIII).
5. **Communicating the results.** Papers I[a], V, VI[a], VII and VIII are for peer group/scientific audiences (expert audience), but are not easily digestible by other audiences for decision making or engagement (lay or managerial audience). I developed Paper II to present the results for decision makers (managerial), with the use of summary maps and infographics to translate the main outcomes from our work. Within the *Coffee Atlas of Ethiopia* (Paper IV[a]), I present the present-day landscape of coffee-growing/coffee-growing suitability Ethiopia, which was intended for the lay and managerial audience, giving detailed locations of the existing coffee landscape and environmentally suitable areas for coffee (wild and cultivated). The *Coffee Atlas of Ethiopia* will enable effective decision making (e.g. investment in new coffee producing areas, farm intervention projects, tree planting), help to market Ethiopian coffee (many new coffee origins are enumerated), and it should be attractive to coffee (and other) tourists. It is the most detailed and most accurate publicly available map of Ethiopia, to date. Beyond these manuscripts, the findings from this PhD have been very widely reported in the print, radio, television, web and social media. Where accessible, these are summarised in Appendix VII.



Figure 16. Sorting and grading of coffee in Ethiopia. Image: Aaron Davis.

2. Contribution to Knowledge and Impact

Here I review the contribution to knowledge and summarise the impact of the thesis outputs. Impact has many different meanings to different audiences with diverse motivations (see section 9 in the extended abstract). More detailed impact for the published (and therefore to some degree measurable) scientific papers is presented in Appendix VII and economic impact is reviewed in Appendix VIII.

Paper I[a]

This paper sets the foundation for the PhD. Before its publication, precise modelling of the influence of climate change on Arabica coffee was very limited: there was very little data available for wild populations of this species and such data were not used for distribution modelling for the species. This paper provided the inference that here was a likely response by Arabica coffee in Ethiopia under a changing climate. The publicity and impact (see Appendix VII for details) from this paper were huge (both within media, on the web and academically) and helped to secure the funding for the work within this PhD. Paper I was taken seriously in Ethiopia, and was incorporated in governmental-level documentation, and Ethiopian media.

Papers II and III

These two publications detail the methods, drivers, results and future strategy for the project *Building a Climate Resilient Coffee Economy for Ethiopia*. Paper II is by far the most comprehensive study to date for Arabica coffee in Ethiopia under climate change, and perhaps for any single crop species globally. It covers both the wild and cultivated coffee in Ethiopia and is novel for plants in combining SDM modelling and migration scenarios for future predictions. It was published in the relatively new *Nature Plants*, which has an impact factor of 10.3. It also made the front cover of the journal.

Paper III summarises the results from the analyses of Paper II, but also includes deforestation figures, coffee area projections under climate change, as well as summarising the strategies required for sustainability under climate change (adaptations and investments).

As with paper I[a], the publicity and impact for these outputs has been considerable, with reporting in the major press, radio, TV and social media (see appendix VII for details). Both papers have been very well received by peers and the coffee sector, prompting in-country discussion at the academic and governmental level (Appendix VII). Our work went directly to the most senior levels of Ethiopian government, via inclusion in an independent policy document road-mapping the future of coffee production in Ethiopia. Economic impact is addressed in Appendix VII.

Paper IV[a]

This Coffee Atlas of Ethiopia has only just (April 2018) been published, so its impact cannot yet be assessed. It was designed to show the precise details of the coffee landscape across Ethiopia, and coffee farming suitability. It should contribute directly to the planning of coffee farming and coffee farming interventions, and the conservation of wild Arabica coffee. It should also assist with reforestation and farming investment in Ethiopia. It demonstrates the detailed mapping and cartography that was used within our work. To date we have received a very enthusiastic reception, selling 300 copies immediately to the coffee industry; a further 300 copies have been freely distributed in Ethiopia to key stakeholders (government organisations, NGOs, civil societies, and trade).

Paper V

This manuscript represents a major analysis on the use of area of occupancy (AOO) and the modifiable area unit problem; the findings, methods and recommendations are likely to be fundamental to this field of science. At the least it will change the way AOO is calculated for conservation assessments, but it will also have implications for the methods spatial scientists use to calculate any areal grid metrics (as happens with any spatial raster image or ground sampling). In summary, I believe the research reported in this paper will have far-reaching influence and longevity.

Paper VI[a]

This is a methods and code manuscript paper, which follows on from my previous work in ArcView (Willis, Moat and Paton, 2003; Moat, 2007) and GeoCAT (Bachman *et al.*,

2011; Moat, Vizzuality and Bachman, 2017), bringing it up to date and making it available within the statistical package R (R Core Team, 2016). The work was undertaken to allow all the data from Paper II to be batch-processed (using multiple generation-length and all multiple climate models) to give a final extinction risk assessment for *C. arabica* (Papers VII and VIII). In addition to calculating the various spatial metrics used for extinction risk, it also provides a simple and automatic area geographic projection wizard following Snyder, (1987) and Šavrič, Jenny and Jenny (2016). This R package was released in January 2017 and using https://dgrtwo.shinyapps.io/cranview/ we can view the number of downloads per day. Since it was released six months ago, the package has been downloaded over 700 times, presently averaging 155 downloads per month (https://cranlogs.r-pkg.org/badges/rCAT).

Papers VII & VIII

These papers bring together all the work of the previous papers, to provide an extinction risk assessment for *C. arabica*. This is the first time this species has been assessed, and the first time a plant species has been comprehensively assessed for extinction risk under climate change. The main outcome of this research is that *C. arabica* will now be categorised as an Endangered species, and therefore on the extinction 'watch list'. The paper also reports that generation length is a critical factor in determining extinction risk in plants. Paper VII has been accepted (May 2018) for publication in *Global Change Biology*, whilst paper VIII is in submission with IUCN. We have yet to see the impact, but I would anticipate much media interest.

All coffee publications (I[a], II, III, VI[a], VII and VIII)

All the coffee papers represent a substantial contribution to the knowledge of the species and its fate under climate change. The papers and the data form a comprehensive baseline, which can be used to assess the future of this species. This baseline provided by the PhD studies is powerful and will allow the species' response to climate change to be monitored, its extinction risk tracked, and decisions made on the future of the cultivated species in Ethiopia, which I hope will allow the species and the country to prosper.



Figure 17. Ripe coffee fruits (cherries), freshly picked in Ethiopia (image: Justin Moat).

Around 25% of Ethiopia's population rely on coffee for their livelihoods

3. Critical review and future work

I have shown that my research has been a major contribution to our knowledge of coffee and is also a valuable contribution to how we calculate and use area of occupancy (AOO) and understand the modifiable areal unit problem in ecology and conservation. But of course, in order to do such an extensive analysis, some areas have been dealt with superficially and broad assumptions have had to be applied. To deal with the process of publicising science, the more novel and attractive science needs to be prioritised, leaving some of the more obvious results and observations hidden from view.

Coffee in Ethiopia

I have gathered a considerable amount of data and knowledge on coffee in Ethiopia, but there are still many areas that remain very poorly known and untested; for some aspects of the subject we have no information at all. Some of the areas that I would highlight for further investigation include:

- **Coffee productivity levels:** These are very poorly known in Ethiopia, particularly as c. 50% of the coffee produced is sold in-country (manuscript IV[a]). Crop figures are recorded at a few regional centres, but these cover huge and varied areas of the coffee landscape (manuscript IV[a]). Within my research I used niche suitability to understand the coffee-growing areas (manuscripts II and III), and I extrapolated these classes to the number of wild individuals (manuscript VII and VIII). At this level of enquiry, and for understanding the potential changes in population number, this is sufficient. But to really understand the quality and quantity of coffee produced, we need much finer resolution (in space and time) production figures per unit area, for different regions and coffee-growing environments.
- **Conditions for coffee growth.** I have presented results that only use climatic variables (temperature, rainfall and seasonality) and forest cover. These predictions, although shown to be accurate at the scale of 1 km (manuscript II), miss some of the on-ground conditions. Soil types, soil fertility, levels of shade, type of shade, plant variety and hydrology all play very important parts

in coffee growing (manuscripts II, III and IV[a]), and require finer-scale measurement.

- **Conditions for coffee productivity.** There are many other factors that influence coffee productivity beyond climate, soil, shade, etc. I highlight two possible factors below that could have a major effect or at least need to be understood in more detail in future studies.
    - **The biennial cycle** is a major feature of Ethiopian coffee production, which can influence coffee production tenfold. A good production with high yield (an 'on' year) is followed by a year of very poor or no yield (an 'off' year) (see Paper IV[a] and (Gilbert, 1938)). This cycle is relatively well known, but its interaction with local conditions and climate is poorly understood.
    - **Farming methods in Ethiopia:** There are multiple methods of farming, which can influence the production levels of the crop; planting densities, pruning, weeding, feeding and mulching will all influence the plant health and production levels of coffee (Paper IV[a]). Within Ethiopia, most coffee is produced "naturally", with very little intervention (I have been very diligent to work with ground data that do not have any significant intervention, particularly irrigation). But what is not known is to what level farming practices influence the production and quality of coffee and the biennial cycle. For example, how much can mulching or pruning mitigate the effects of climate change or an 'off' year?
- **Effects of the global and local markets.** I have shown that climate is predicted to have a great effect on coffee in Ethiopia (Papers I, II and III). We have seen that unsuitable areas for coffee have been converted to crops that are more lucrative, such as khat (*Catha edulis*) (manuscripts II and IV[a]). Presently, the global demand for coffee and specialty coffee is high, but any changes to this, or the price, greatly influence coffee farming in Ethiopia (and globally). Supply and demand models would be extremely useful and would elucidate the influence of demand and prices on primary coffee production over time.

The above examples show that there are many questions still to be answered. We have started to tackle some of these questions in a Darwin Initiative (DFiD) project, which focuses on the coffee area of Yayu (see Figure 7 for location), where we have trial plots in place to test the effects of pruning and mulching. This project also aims to improve livelihood and biodiversity conservation by directly connecting farmers and the UK coffee sector (Union Hand-Roasted Coffee, London, UK; Figure 22).

Climate change and coffee suitability in Ethiopia

As discussed above, the results and conclusions (Papers II, II, VII and VIII) are primarily based on climatic conditions/space. There are some import additional conditions that climate change will also affect:

- **CO_2 fertilisation effect.** Increases in CO_2 concentrations have been shown to improve leaf and water use efficiency (Rodrigues *et al.*, 2016). I have argued (Paper II) that coffee is a climate-sensitive species with low adaptive capacity (Papers I and II), and as such any benefits from elevated atmospheric CO_2 will be outweighed by soil water constraints (drought; in its duration, timing and severity) in the longer term (Paper II). Recent research has progressed the thinking on CO_2 enrichment. Rahn *et al.* (2018) suggest that CO_2 enrichment could give a 13–21% increase in coffee productivity; Ramalho *et al.* (2018) show that any bean quality change from temperature increase could be mitigated by elevated CO_2; whilst Dubberstein *et al.* (2018) show that raised CO_2 levels will show a positive impact on coffee production. However, most of these studies are conducted in an environment where water supply is either not or only marginally restricted. As Dubberstein *et al.* (2018) point out "Even so [with elevated CO_2], some mitigation strategies will be necessary to alleviate the impacts of elevated temperature and/or drought stress on coffee trees". Generally, almost all of the above studies concede in some way that elevated CO_2 levels will only be beneficial in an environment where the soil is close the or at full water capacity. All of the work cited above is either modelled or performed in laboratory/greenhouse conditions, with no water stress. Our observations on the ground show that coffee productivity and

coffee survival in the Harar region has been declining over many decades, with many farmers abandoning coffee farming altogether; our models show this area will be suboptimal (marginal to unsuitable) by at least 2030. Present day and projected CO_2 concentrations will not be enough to mitigate increases in temperature and water scarcity in the area. Further work is needed to determine CO_2 fertilisation effects in real-world (field) condition and production systems.

- **Effects of climate change on forest, canopy cover and composition.** My models largely assume static forest cover, i.e. that canopy cover is present and consistent through time. This is a simplistic view as forest composition and cover will change with climate (and deforestation; see below). Most tree species in the coffee forest niche have very long generation times, so any change will take many decades to be evident (Bertrand *et al.*, 2011). In general, I feel the above assumption will have only a small effect in the short-term, but in the longer-term modelling and monitoring is needed to understand the potential change in forest cover and composition under climate change.
- **Other effects of climate change.** The possible outcomes of a changing climate are numerous, but ones that could affect coffee include:
    - Influence of changing climate on people. These changes are not easy to predict or model, but there could be an influence due to famine (driven by conflict and lack of rainfall), which would drive migration to the southern area of Ethiopia from South Sudan, Sudan, Somalia and the Ethiopian Harar and Somali regions, resulting in accelerated deforestation and land-use change in the South West coffee area (Papers III and VIII).
    - Water shortages are likely to increase, which in turn would result in depleted water tables and water levels in dammed areas.
    - Pests and diseases of coffee will change under a changing climate. Coffee berry borer (*Hypothenemus hampei*) incidences are expected to increase with climate change in Ethiopia (Jaramillo *et al.*, 2011). On the other hand, some pests and diseases may lessen under new

climatic conditions. More work is needed to understand possible changes in other pest and diseases, under climate change of the coffee crop in Ethiopia.

- Increase in extreme weather events. It has been predicted (and there is some evidence that this is already occurring) that the number of extreme weather events will increase, or at least we will be more vulnerable to these extreme events (Easterling *et al.*, 2000; Rosenzweig *et al.*, 2001). Extended hot periods will kill coffee and even short periods of temperatures over 38 ^{o}C can result in aborted flowers and fruit (Paper VI[a]). As temperatures increase, incidences of fire are also predicted to increase (Easterling *et al.*, 2000). Periods of drought or the late arrival of the wet season can easily result in the loss of a season's coffee crop. Finally, periods of hail or extreme rain can strip the plants of flower or foliage (Paper VI[a]). Unfortunately, there is little recorded (beyond anecdotical evidence) on the effects of these extreme weather events on coffee, but an understanding of implications for coffee production could be highly insightful.

Deforestation in Ethiopia

Within the models, I do not directly consider deforestation trends for the region (although it is shown and discussed in Paper III). Within Paper VII, I show that that one of the most serious of threats to wild coffee is deforestation, but that no study to date has tackled this specifically for coffee forests. Historical deforestation rates in Ethiopia are very high and ongoing (Reusing, 1998, 2000; World Resources Institute, 2014) and if these rates were applied to coffee forest they would support the extinction risk assessment of Endangered as derived from the climate change analysis in Paper VII. I have suggested (in Paper VII), that this could be rectified with a dedicated study of the temporal changes in suitable coffee forest (Moist Evergreen Afromontane Forest (MAF) and Transitional Rain Forest (TRF) types; Friis, Demissew and Breugel 2010) across the region, using remote sensing data and techniques.

Global climate change models

For the future predictions I have relied on the GCMs produced by multiple institutions, for many future scenarios and dates. To make these data more useful for the SDMs, I used downscaled (from ~250 km to 1 km) datasets (Ramirez-Villegas and Jarvis 2010). We found that these GCMs are in general agreement on temperature changes, but precipitation was quite different for different GCMs with little or no overall trend (Paper II). When I started the initial work, only the CIMP3 GCMs were available, now all CMIP5 GCMs are available as downscaled data. I show in Paper II that the newer GCM and scenarios are unlikely to make much difference to the outcomes. Nonetheless, as new GCMs and new emission scenarios are refined or adopted it would make sense to rerun previous modelling, to be up-to-date and to refine the modelling to the latest scenarios, especially given the importance of water availability to the temperature effect on Arabica coffee.

For the downscaling I used the simplest method (i.e. delta, where you apply the difference comparing present-day to the future (Ramirez and Jarvis, 2008)). I feel this is the best method to understand the changes that are projected (see Figures 18–21). It is a very simple method and changes are easy to interpret. There are many methods proposed for downscaling (Trzaska and Schnarr, 2014), and it would be interesting to see what difference this would make to the predictions, but there still exists the issue that you cannot test the accuracy of a future projection (at least not until after the fact).

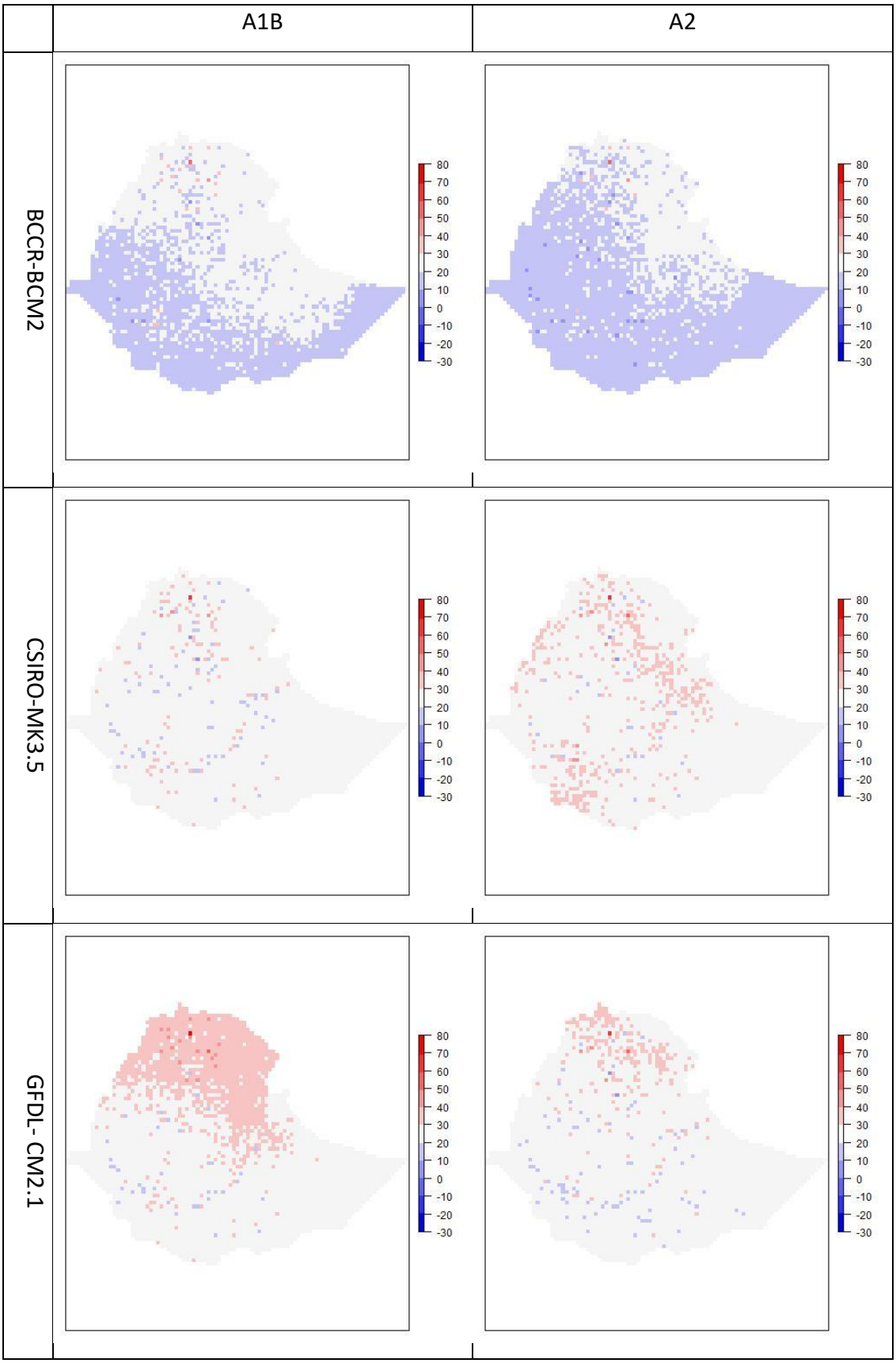


Figure 18 Mean annual temperature change (BIOCLIM 1) (1960 – 1990 compared to 2040 – 2069), units are degrees centigrade x 10 (i.e. 20 is a 2 degree increase in temperature)

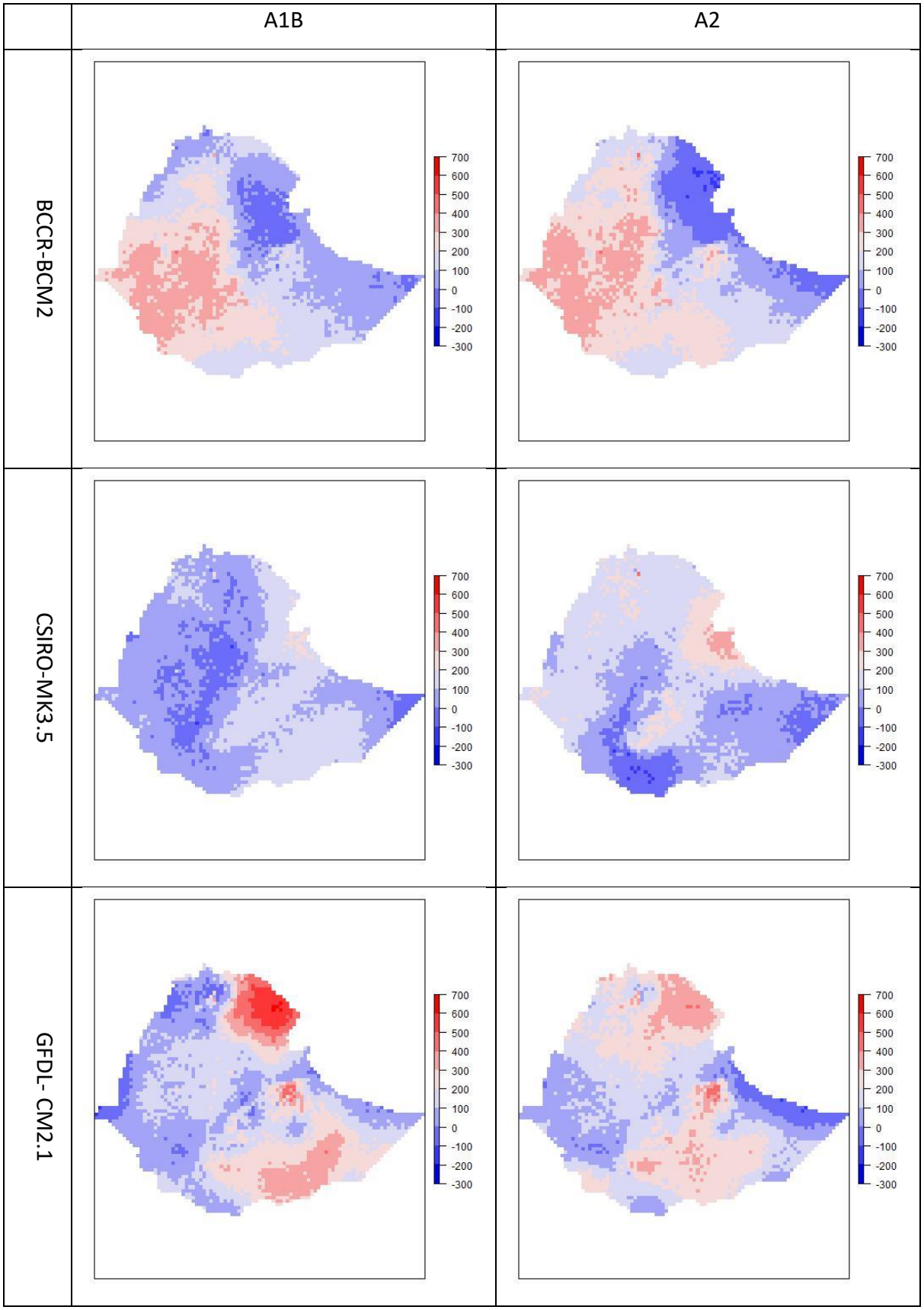


*Figure 19. Mean annual change in temperature seasonality – BIOCLIM 4 (1960 – 1990 compared to 2040 – 2069). standard deviation (in degrees C) *100*

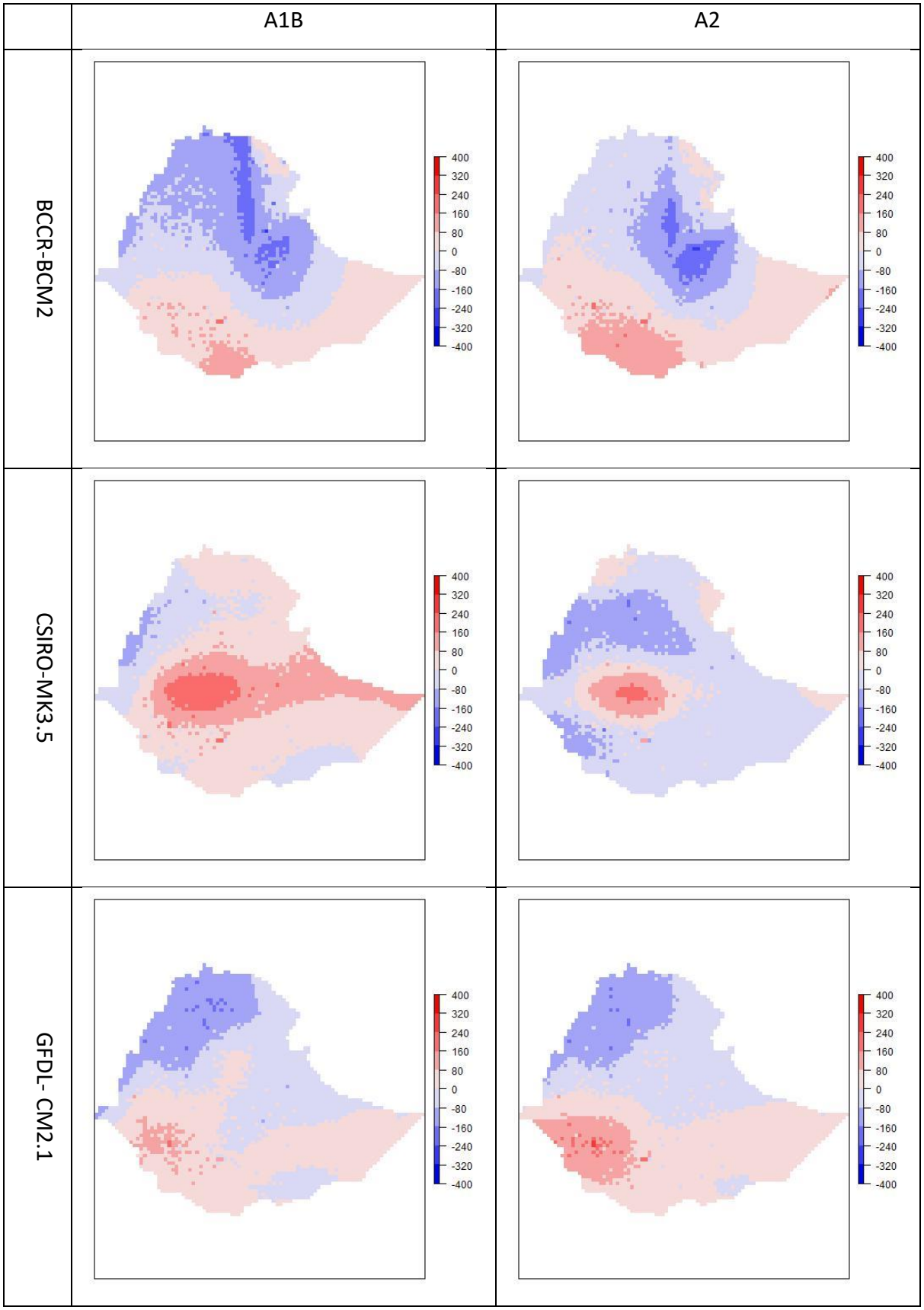


Figure 20 Mean annual change in precipitation – BIOCLIM 12 (1960 – 1990 compared to 2040 – 2069). Units mm of rainfall

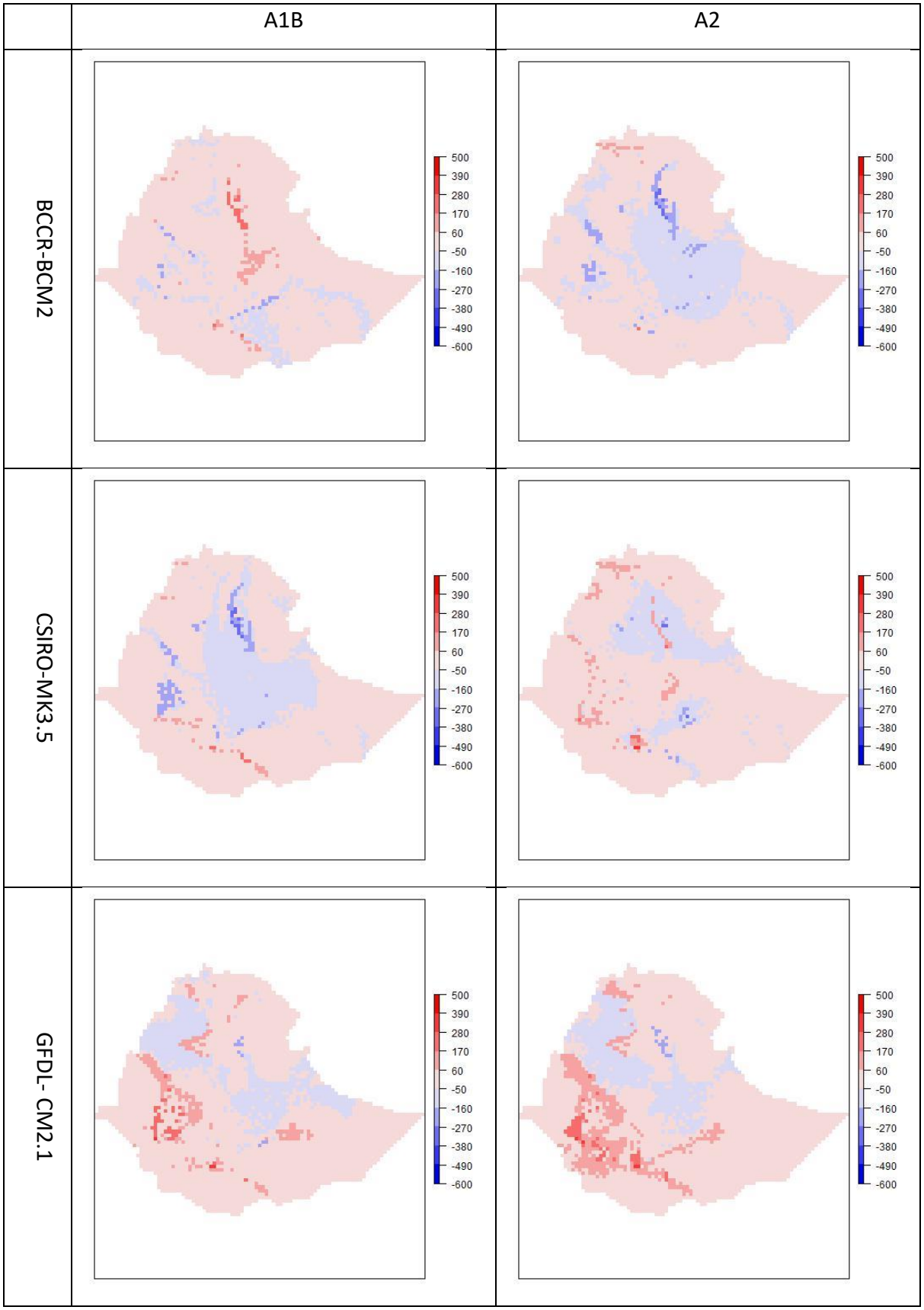


Figure 21 Mean change in precipitation of the warmest month – BIOCLIM 18 (1960 – 1990 compared to 2040 – 2069). Units mm of rainfall

SDM Methodology

The use, issues and caveats of SDMs are covered in Paper II and by others (e.g. Wiens *et al.*, 2009). For Arabica coffee in Ethiopia, we have a large dataset (3070 Points), which is a rarity compared with many models for plant species. This dataset still has its biases and shortcomings (for example; abundance is rarely recorded), but its size and coverage allow some of the caveats, methods and bias to be tested to assess their influence on the final modelling.

Future predictions for coffee suitability

I needed to reduce the number of GCMs and scenarios used in the modelling, as processing time was becoming excessive. With the increase in computing power and the availability of multiple core clusters, with parallel processing, this should no longer be a major hurdle. Also, and as mentioned before, the latest (CMIP5) downscaled GCMs are now available. I would advocate that researchers use all GCM and RCP scenarios in their research. However, there is an interesting aside to this: having to reduce the number of GCMs did give me greater insight into each GCM and the drivers of change we observed in our models (Paper II).

Area of occupancy and the modifiable areal unit problem

I have tackled this area using various means, within the constraints of the IUCN's doctrine. Regardless, there is still a fundamental question: is area of occupancy (AOO) the best measure for species' areal extent? Presently the measurement of AOO is very scale and data dependent (Hartley and Kunin, 2003). Indeed in the past (Willis, Moat and Paton, 2003) I have advocated for the use of other methods (Rapoport's mean propinquity (Rapoport, 1982)) as have others (Hernández and Navarro, 2007). Another question is: is minimum AOO really the best measure to report? I have shown (Paper V) that AOO can have multiple values following a binomial distribution, for which the minimum is probability driven (i.e. the more data and methods you have, the more variable AOO will be), this suggest that minimum AOO may not be a sensible measure to record. Indeed, when considering climate change within Paper VII, I did not report the worst case (or precautionary rule as IUCN suggest), which gives coffee the extinction risk vale of Critically Endangered, but rather I report at where 50% of the metrics gave an assessment of Endangered or greater.



Figure 22. Coffee packaging, as used in the UK for our Darwin Initiative project in Yayu, Ethiopia (Image: Union)

4. Conclusions

This thesis represents a substantial contribution to the knowledge of Arabica coffee, predicting its fate under climate change, both for the wild species and farmed coffee in Ethiopia. For the prediction methods, I used existing methodologies, but I innovatively combined these, both with remote sensing (for coffee forest cover) and possible future migration scenarios for the species. Whilst predicting extinction risk for Arabica coffee, I have tackled a pressing need to understand how the modifiable areal unit problem might affect species' areal measurement, using different grid shapes and orientations. Finally, I have applied the climate change predictions for Arabica coffee with areal measurement, generation length and population estimates to give wild Arabica coffee an extinction risk assessment of Endangered.

Of course, with such an extensive analysis, I have had to take some short-cuts, with certain assumptions and caveats. These include possible influence of soil, CO_2 fertilisation and other outcomes of climate change (e.g. on canopy cover, pests and diseases, and human geography). I have shown that it is possible to predict a species' fate under changing climate; the challenges and uncertainties in doing so are large, but not insurmountable. My predictions for coffee farming in Ethiopia show that with no interventions there could be a reduction of up to 60% of its suitable area by the end of the century, but that if interventions are made there is a possibility of increasing the production area of coffee by at least fourfold. This has major implications for coffee conservation and production in Ethiopia. Two of my coffee papers (and the associated media outputs) tackle this implication, conveying the results, findings and recommendations to a wider audience (policymakers, decision-makers, producers, farmers and the general public), allowing them to make better and more informed decisions. My final coffee paper puts wild coffee at the forefront and shows that the fate of wild coffee will be intrinsically linked to the influence of climate change and forest cover change, but also highlights that calculating generation lengths is critical. My investigations into the areal measurements for AOO, show that it can be highly variable with different shape and orientation, and that this has major implications when reporting areal measurements or changes in these measures. From this analysis, I have presented novel, repeatable and quick algorithms, which return the variation in area measurements, as a well as finding the minimum area.

The increase in available computing power, data and techniques even in the brief period of this PhD has been considerable. For Paper I, appropriate data were only available for one GCM; we now have multiple downscaled GCMs available (presently over 23), for many time periods. I have also moved from using one species distribution modelling method (Maxent) to multiple methods, combining them into ensemble models. Satellite imagery is becoming more easily available, cheaper (free in many cases), with greater temporal, spectral and spatial resolution. We have moved from CMIP3 models to CMIP5 (although I and others have shown they make only minor differences to our results). Future work could use this increase in computing power in combination with new datasets to predict the fate of Arabica coffee using all GCMs and future climate scenarios, not just the selections I used here. The increasing availability of archived satellite imagery could be used to assess the extinction risk of coffee species with the inclusion of forest change, which is likely only to help to consolidate the extinction risk of Endangered under climate change for wild Arabica coffee.

We now have a much better understanding of the short- to long-term fate of wild Arabica coffee – we now have a robust conservation assessment in place and detailed baseline data for the monitoring of this important species of commerce and society. To quote myself (Moat 2017, press release, Royal Botanic Gardens, Kew):

"Under a changing climate, business as usual is not an option. Timely, informed, science-based decision making is required now"



Figure 23. Coffee ceremony, Ethiopia (image: Justin Moat).

Coffee-drinking is an intrinsic part of Ethiopian society; half the coffee produced in Ethiopia is used in the domestic market.

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Figure 24. Coffee production in Gololcha, Ethiopia (Photo: Justin Moat)

Appendices

Appendix I: Other pertinent authored publications

Paper I[a]. The impact of climate change on indigenous Arabica coffee (*Coffea arabica*): predicting future trends and identifying priorities.

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The Impact of Climate Change on Indigenous Arabica Coffee (*Coffea arabica*): Predicting Future Trends and Identifying Priorities

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Abstract

Precise modelling of the influence of climate change on Arabica coffee is limited; there are no data available for indigenous populations of this species. In this study we model the present and future predicted distribution of indigenous Arabica, and identify priorities in order to facilitate appropriate decision making for conservation, monitoring and future research. Using distribution data we perform bioclimatic modelling and examine future distribution with the HadCM3 climate model for three emission scenarios (A1B, A2A, B2A) over three time intervals (2020, 2050, 2080). The models show a profoundly negative influence on indigenous Arabica. In a locality analysis the most favourable outcome is a c. 65% reduction in the number of pre-existing bioclimatically suitable localities, and at worst an almost 100% reduction, by 2080. In an area analysis the most favourable outcome is a 38% reduction in suitable bioclimatic space, and the least favourable a c. 90% reduction, by 2080. Based on known occurrences and ecological tolerances of Arabica, bioclimatic unsuitability would place populations in peril, leading to severe stress and a high risk of extinction. This study establishes a fundamental baseline for assessing the consequences of climate change on wild populations of Arabica coffee. Specifically, it: (1) identifies and categorizes localities and areas that are predicted to be under threat from climate change now and in the short- to medium-term (2020–2050), representing assessment priorities for *ex situ* conservation; (2) identifies 'core localities' that could have the potential to withstand climate change until at least 2080, and therefore serve as long-term *in situ* storehouses for coffee genetic resources; (3) provides the location and characterization of target locations (populations) for on-the-ground monitoring of climate change influence. Arabica coffee is confimed as a climate sensitivite species, supporting data and inference that existing plantations will be neagtively impacted by climate change.

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Introduction

Coffee (*Coffea* L.) is the world's favourite beverage and the second-most traded commodity after oil. In 2009/10 coffee accounted for exports worth an estimated US$ 15.4 billion, when some 93.4 million bags were shipped, with total coffee sector employment estimated at about 26 million people in 52 producing countries [1]. Arabica coffee (*Coffea arabica* L.) and robusta coffee (*C. canephora* Pierre ex A.Froehner) are the two main species used in the production of coffee, although the former is by far the most significant, providing approximately 70% of commercial production [1]. The productivity (green bean yield) of Arabica is tightly linked to climatic variability, and is thus strongly influenced by natural climatic oscillations [2]. The stated optimum mean annual temperature range for Arabica is 18–21°C [3], or up to 24°C [4]. At temperatures above 23°C, development and ripening of fruits are accelerated, often leading to the loss of beverage quality [5], although in some locations higher temperatures (24–25°C) can still produce satisfactory yields of beans, such as in northeast Brazil [6]. Continuous exposure to temperatures as high as 30°C leads to stress, which is manifest as depressed growth and abnormalities, such as the yellowing of leaves and growth of tumours on the stem [7]. In regions with a mean annual temperature below 17–18°C growth is also depressed [8]. Occurrence of frosts, even if sporadic, may strongly limit the economic success of the crop [5]. The relationships between climatic parameters and agricultural production is further complicated because these environmental factors influence the growth and the development of the plants in different ways during the various growth stages of the coffee crop [2].

The Intergovernmental Panel on Climate Change [9] predicts that best estimates for average global temperatures, across all scenarios, will be between 1.8°C to 4°C by the end of the twenty-first century. Global temperatures have increased by an average of 0.74°C (+0.56°C to 0.92°C) in the last 100 years (1906–2005), and this increase appears to have accelerated since the 1970s [9]. On this basis it has been forecast that the sustainability of the coffee industry faces serious challenges in the coming decades [2,10–14]. The evidence from coffee farmers, from numerous coffee growing

regions around the world, is that they are already suffering from the influences increased warming [11,14]. Precise modelling of the influence of climate change for either Arabica or robusta is limited. So far work has been largely restricted to climatic envelope forecasting based on optimum and suboptimum (tolerable) temperature and rainfall averages [14,15], although in Sao Paulo (Brazil) future climatic scenarios have been applied across the federal agricultural zoning system for cultivated Arabica [10].

Indigenous Arabica plays a key role in coffee production in Ethiopia [4] and has an intrinsic value as the storehouse of wild coffee genetic resources, with an estimated value to the coffee industry of 0.5 to 1.5 billion US$ per year [16]. Ethiopia is the fifth largest global exporter of Arabica and the main producer of coffee in Africa; coffee accounts for c. 33% of Ethiopia's total export earnings [1]. The largest and most diverse populations of indigenous (wild) Arabica occur in the highlands of south-western Ethiopia ([4,17–21], but the native range includes satellite population in south-eastern South Sudan (Boma Plateau) and northern Kenya (Mt Marsabit), at altitudes between 950 and 1950 m, although 1200 m is the most frequent lower altitude limit [22]. By comparison, the indigenous distribution of robusta coffee includes much of tropical Africa, from Guinea to western Tanzania, at altitudes of 50–1500 m [22]. The genetic diversity of wild Arabica populations far exceeds that of cultivated varieties used in crop production and accessions held in germplasm collections [21,23–27]. The wild populations also have high functional diversity in terms of disease [28], and pest and drought tolerance [29–31]. As part of a future-proofing resource, and especially for providing genetic potential for mitigating climate change, indigenous populations are perceived as a key resource for the medium- to long-term sustainability of Arabica production [16].

In this study we model the indigenous distribution of Arabica for the present day, and for the future under the influence of climate change until 2080, in order to identify priorities (for *in situ* and, and *ex situ* conservation, monitoring, and future research) and facilitate appropriate decision making. We use bioclimatic modelling based on locality data, in combination with future climate change scenarios across predetermined time intervals until 2080. Bioclimatic models typically compare large-scale species distributions (distribution maps) against present-day modelled climate parameters, in order to generate a predictive statistical model [32]. When a model is deemed successful and robust, the future distribution of a species can be projected over a suitable time frame using climate change scenarios, such as those generated by the Met Office Hadley Centre, or the Commonwealth Scientific and Industrial Research Organisation (CSIRO), to provide a future assessment of distribution under changed environmental conditions [32]. Bioclimatic- (or niche-) based modelling has been widely used in the last ten years to predict the potential impacts of climate change on species distributions all over the world [33]. This type of modelling has been judged as ecologically naive by some [34,35], as species occurrence is dependent not only on climate, but also on ecological processes such as dispersal, colonization, and complex interactions with other organisms. In this respect, process based modelling, including ecological data, are often favoured on theoretical grounds, by injecting ecological realism into the modelling framework [32]. In reality, species-specific process-based modelling remains scarce at the continental and regional scale [33,36], owing to the difficulties in acquiring and combining data for analysis. It has been pointed out that the use of both approaches, with their own caveats and advantages, are crucial in order to obtain robust results, and that comparisons among models are needed in the near future to gain accuracy regarding predictions of range shifts under climate change [33].

Materials and Methods

Ethics

All necessary permits were obtained for the described field studies in South Sudan. Permits and permission for study on the Boma Plateau were agreed and obtained through the John Garang Institute of Science and Technology in Bor, Jonglie State, South Sudan, following agreements with the South Sudanese government. Permission to visit sites in the Boma Plateau National Park was agreed through the Wildlife Conservation Society (WCS), acting on behalf of the Jonglie State government and relevant landowners.

Mapping data

Locality data for naturally occurring Arabica were derived from three sources: (1) field survey data for populations in Ethiopia (648 datapoints; data collected 2000–2006, T. Gole, unpubl. data); (2) records of wild populations from literature (18 datapoints; from 1941 [37] and 1964/5 [38]); and (3) herbarium specimens (14 datapoints; collections made 1941–1984). Herbarium specimens were surveyed at the Natural History Museum, London (BM), Royal Botanic Gardens, Kew (K), the Museum of Natural History, Paris (P), and the herbarium of the Wageningen branch of the National Herbarium of the Netherlands (WA; [39]). A total of 751 locality records were databased. Data records lacking co-ordinates were geo-referenced using BioGeomancer Workbench (version 1.2.4; http://bg.berkeley.edu/latest [40], paper maps, and in some cases via interview with regional specialists. All co-ordinates, including those that stated the use of a global positioning system (GPS), were carefully verified and/or error-corrected using Google Earth (Version 5; ©2010 Google). Each specimen record was assigned an estimate of confidence, given as the diameter of a circle in km (normally 0.01 to 0.05 km for GPS readings (made at the time of data collection), and 1 to 100 km for estimated historical localities). The field survey data (719 records) provided 89.7% of the data (accuracy up to 50 m diameter); and other data (specimens and literature) 10.3% of the records (9.5%: accuracy of 1–5 km diameter; 0.83%: the six localities mentioned below). Ambiguous records (i.e. those that could not be geo-referenced to a specific locality), and those outside a 5 arc minutes resolution (c. 5 km diameter), were rejected for the purposes of modelling. In total 713 records were used (six localities rejected: three data records with no estimable geo-reference; three with over 5 km diameter accuracy). The accepted data represents 349 unique localities (i.e. no duplication of localities for identical geo-referenced points; referred to as 'localities' in the main part of this contribution), were used. ArcGis 10 [41] was used for all mapping outputs.

Predictive mapping/ecological niche modelling

MaxEnt software (version 3.3.3a) was used to create predictive maps of species occurrence (presence-only; Figures 1 and 2) on the basis of our occurrence data and environmental layers [42–44]. MaxEnt has been found to give the best result of all the modelling algorithms available with presence only data [45–47] and is frequenly used with herbarium and other collection-based data. This class of environmental (or ecological) niche model (ENM) makes use of a correlative model of the environmental conditions that meet a species ecological requirements and predicts the relative suitability of habitat [48]. The ecological requirements are represented by environmental grids or bioclimatic variables (e.g.

temperature, precipitation), which are combined to determine areas and environments that adhere to the species niche, which are manifest as positive areas on the map. The BIOCLIM variables [49] (bioclimatic variables representing annual trends, seasonality and extremes of the environment; accumulated from weather station data from the 1961–1990), accessed via the WorldClim website (http://www.worldclim.org/bioclim. Accessed 2012 Jan 25), were used as grid data at 30 arc seconds resolution (approximately 1 km×1 km). To reduce the processing overhead and data storage, the data was clipped to Africa only. We used the default settings in MaxEnt, which have been shown to give robust and reliable results [44]. The initial models of predicted distribution were tested by omitting 20% of the samples (39 sample points for testing and 158 to produce the model), to gauge the robustness of the models. Area under the curve (AUC), jackknife, analysis of variant contribution, and response curves were also calculated by MaxEnt for further analysis. Preliminary iterations of the models allowed us to identify doubtful outlying localities (i.e. where predictions were very low), and these were corrected where necessary (e.g. geo-referencing errors). A low predictive value was identified for the populations on Mt. Marsabit (Kenya), and so two independent data sets were used, one with and one without Mt. Marsabit.

Spatial sorting bias can give a false impression of model fitness by inflating AUC values [50]. We initially accounted for spatial sorting bias by removing all duplicate localities, (i.e. those with identical georeferences: 713 data records were reduced to 349 unique localities, representing a reduction of 48.9% of the sampling), then these 349 localities were reduced to 197 samples (only one per 1 km grid cell) for the MaxEnt modelling. Then, to more fully test for spatial sorting bias and to check the robustness of the models, further models were produced with spatial sorting bias removed, and for only the core region. Spatial sorting bias was removed by only including points that were separated by at least 0.2 of a degree (c. 22 km), and then checked using ArcGIS 10 [41] average nearest neighbour, which gives a clustering qualification, from clustered, to random, to dispersed. The original 197 samples were highly cluster, but after re-sampling (22 samples points remaining) the points were spatially random. These 22 points were remodelled in MaxEnt, both for the whole of Africa and for a very restricted core region. It should be noted that removal of the bias in this way was only done to test the fitness (comparing AUC and results) of the models; the rest of the analysis was performed using the 349 unique localities (of which 197 were used as the samples for MaxEnt).

Predictive maps represent potential maps of distribution, not the actual distribution of a species: they show where the ecological niche is potentially suitable for the species. The species may not actually occur in this predicted area, for any of the following reasons. (1) The predicted area will include niches that are no longer suitable for the species, because the vegetation has been drastically altered (e.g. deforestation, agriculture). (2) There is niche saturation, e.g. another species or many species already occupy that niche. (3) The models are incorrect due to inaccuracies and weak resolution in the recorded environmental data, which is often the case for microclimates. It should be made clear that the original climate data is also modelled, and based on data from a network of global weather stations. (4) The layers used for modelling are not necessarily the drivers for the occurrence of the species, and other environmental factors (which may drive occurrence) have not been included in the model (e.g. soil characteristics, at a suitable resolution). (5) The locality data is inaccurate. For indigenous Arabica, at least the last two of these points should not strongly influence our distribution model, because the predictive model is very robust (see Results) and the data have been carefully verified by careful scrutiny using satellite maps and ground-truthing, respectively. It should also be said that Arabica coffee is closely tied to narrow environmental parameters, and like the vast majority of coffee species [22] it has a restricted and specific distribution. Data for cultivated Arabica confirms these observations, and shows that this species is sensitive to environmental variables, particularly temperature and precipitation [2,6,8]. Soil-water balance is a key factor for the growth of Arabica, although until now this data is only available for the species in cultivation [2,8]. In addition, observation and reported distribution show that coffee species are rarely adventive, are only scarcely found in secondary (regenerating) vegetation, and quickly become stressed in degraded habitats [22]. In general, the family Rubiaceae includes a very high number of narrowly endemic species, which in most species appears to be related to ecological sensitivity [51].

Future mapping/climate change modelling

Future predictive maps for indigenous Arabica were generated using the same BIOCLIM layers as employed in the MaxEnt analysis, with predicted future climate data downscaled using the delta method to 30 arc seconds (c. 1 km×1 km). The delta method interpolates the General Circulation Model generally used in climate modelling at scales of 100 to 200 km using a thin plate spline spatial interpolation method to achieve the 30 arc seconds resolution [52]. The data was provided by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) (http://www.ccafs-climate.org/statistical downscaling_delta/) [52]. The Met Office Hadley Centre (Hadley Centre for Climate Prediction and Research) climate change model, *Hadley Centre Coupled Model, version 3* (HadCM3) [53], a coupled atmosphere-ocean general circulation model, was used for the time intervals 2020, 2050 and 2080 (note these date represent a time windows of ten years either side of the time interval date, i.e. 2020 is an average of the years 2010–2029, 2050 for 2040–2059 and 2080 for 2070–2089), under three emission scenarios of the IPCC Special Report on Emissions Scenarios (SRES) [54]: scenario A1B (maximum energy requirements; emissions differentiated dependent on fuel sources; balance across sources), A2A (high energy requirements; emissions less than A1/FI) and B2A (lower energy requirements; emissions greater than B1). We tried, and subsequently rejected, the consensus forecasting with unweighted average approach [55], because it did not provide any further quality to the analyses. There are several climate models available (e.g. HadCM3, CCCMA and CSIRO) but the HadCM3 model was selected for this study because it is presently the only one that spans the years 2020, 2050 and 2080, for all three scenarios, at the resolution of 1 km. It is also reported to provide good median results for Africa compared with other models [13]. Separate model iterations were run with and without Mt Marsabit (Kenya), nine for each iteration, giving a total of 18 models. Locality data (i.e. the 349 unique localities) were queried against all model combinations, in order to provide a value for each of the localities for each of the models.

For the present day models, based on all localities, thresholds were calculated to cut off at 68%, 95% and 100% of the 349 (unique) localities, i.e. based on their relative values within the niche model. As we do not have a totally normal distribution for the prediction at each sample point, 68% is not quite equal to 1 standard deviation. These thresholds were used to classify each Arabica locality though time, within each scenario, into 68% (optimal), 95% (intermediate [suboptimal]; includes the 68% threshold), 100% (marginal [extreme environments]; includes 68% and 95% thresholds). These thresholds were applied to the models

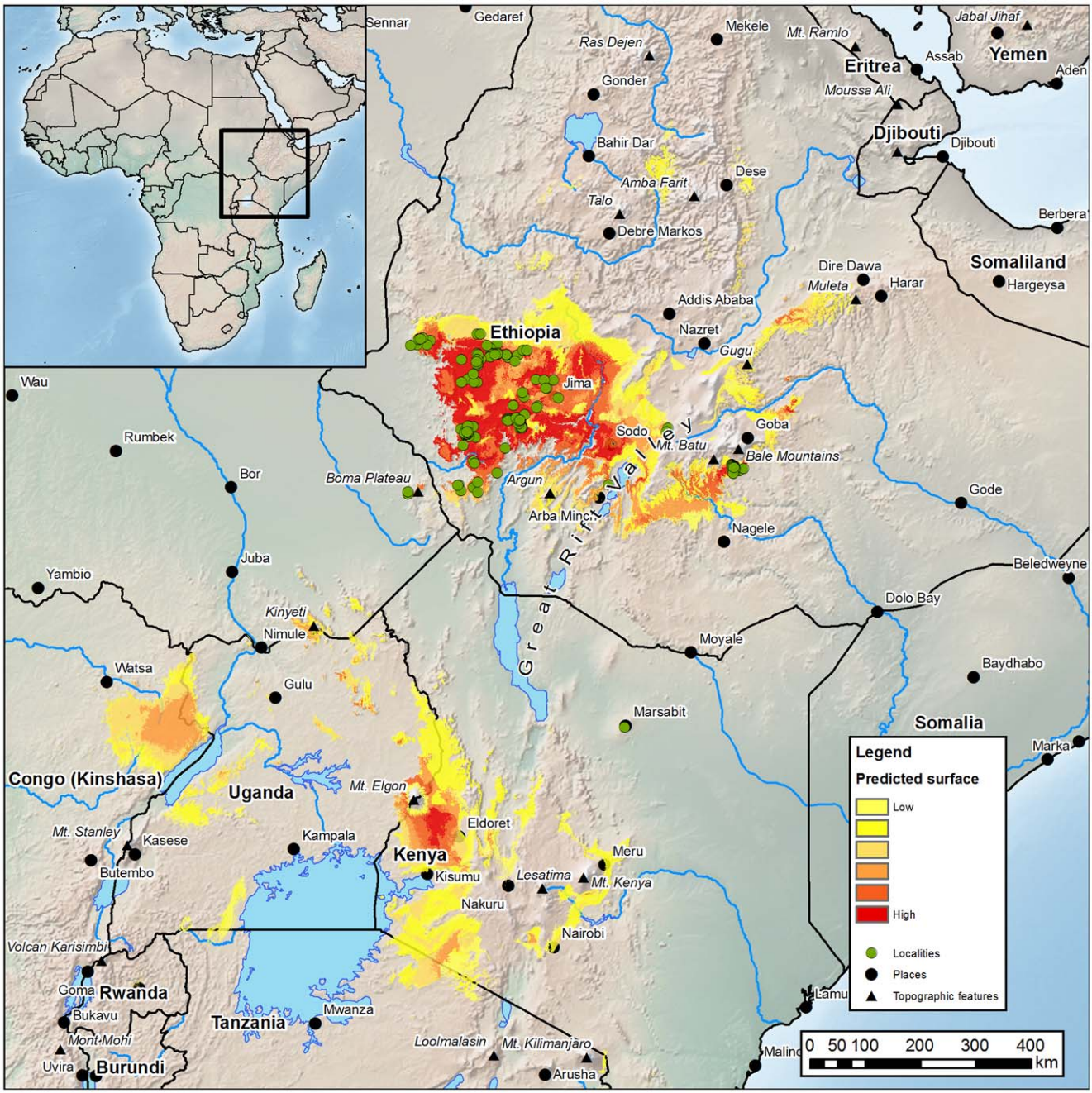


Figure 1. Predicted and actual distribution of indigenous Arabica. Green dots show recorded data-points. Coloured areas (yellow to red) show predicted distribution based on MaxEnt modelling (see internal legend). A context map is given in the top left hand corner.
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to assess the future predicted distribution in terms of bioclimatic suitability (see locality analysis and area analysis, below), with the following assumptions and limitations. (1) Individual plants will not move to different localities that are less suitable than the present day. (2) The area for future modelling was only performed within the core region (i.e. southern Ethiopia and SE South Sudan), in order to reduce the amount of processing and also to limit model spread where there is no control (i.e. no locality data and zero or minimal chance of occurrence). We ran future models including and excluding Mt Marsabit, but either way it made little difference to the modelling. Mt. Marsabit is a considerable distance (c. 500 km) from the main area of Arabica distribution, and is separated from it by a large bioclimatically unsuitable region (low altitude, seasonally dry vegetation). Indigenous Arabica coffee is almost entirely exclusive to the Moist Evergreen Afromontane Forest, and Transitional Rain Forest of Ethiopia [56] and South Sudan [37]. In addition to this, the predictions for occurrence on Mt Marsabit are low. For the future distribution modelling Mt Marsabit was removed from all analyses. (3) It is possible that the Arabica localities used for the modelling are actually now occurring in areas of marginal bioclimatic suitability. This is unlikely given the amount of contemporary locality data we have used, and also because the vast majority of localities have been recorded recently in what is considered to be an optimum

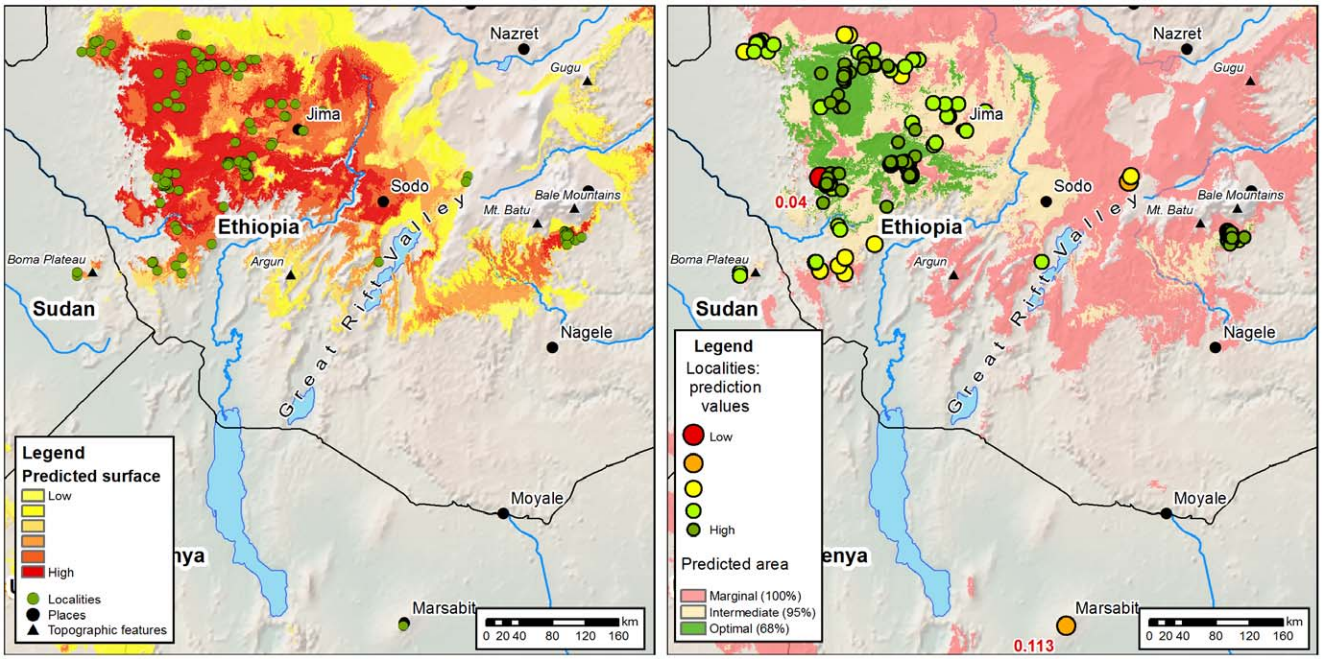


Figure 2. Predicted and actual distribution of indigenous Arabica. Figure 2A. Green dots show recorded data-points. Coloured areas (yellow to red) show predicted distribution based on MaxEnt modelling (see internal legend). Highest predicted area (dark red) indicates 'core region'. Figure 2B. The same map with thresholds of bioclimatic suitability applied at 68% (optimal), 95% (intermediate) and 100% (marginal) to the localities. Prediction values for each locality are represented by colour and size (see internal legend) with values for low predictions labelled in red, superimposed on predicted surface (space) according to the area analysis. Localities with the smallest (dark green) circles represent 'core localities'; highest (optimal) predicted area (green) indicates the 'core region'. See main text for further details.
doi:10.1371/journal.pone.0047981.g002

environment for the species [56,57] (S. Demissew, pers. comm.; I. Friis, pers. comm.;T. Gole, pers. observ; .). (4) Vegetation is not included in the modelling; assumptions based on the predictions assume that the vegetation is intact and will remain so until 2080. This does not represent the current situation and future for remaining natural vegetation in the study area. The forest types holding indigenous Arabica are highly fragmented, and zero land-use change from now until 2080 is totally unrealistic. These assumptions were implemented because remaining (actual) vegetation maps for Ethiopia and South Sudan are not available.

Climate change scenarios (2020–2080) — a locality analysis

The locality analysis uses actual localities, recorded from 1941 to 2006. As explained above, we used 713 records, representing 349 unique localities (i.e. no duplication of localities for identical geo-referenced points; referred to as 'localities' in the main part of this contribution). The localities were used to produce the MaxEnt distribution (reduced to 197 samples for the modelling) for both the locality and area analyses, but in the former the localities were directly analysed against the MaxEnt models through time. For each emission scenario (A1B, B2A, and A2A) a model of future distribution was produced, and then the localities were queried against each scenario and classified into the same thresholds (68%, 95%, 100% and outside 100%) as used for the present day (i.e. the year 2000) predictive models (Figures 3 and 4). For interpretation of the results generated by the locality analysis we need to consider the assumptions used in the downscaling methods when applied to the HadCM3 model [58], which are: (1) changes in climates vary only over large distances, i.e. as large as Global Circulation Model cell size; (2) relationships between variables in the baseline ('current climates') are likely to be maintained towards the future. That is, any generalisations or problems in the original BIOCLIM data will be maintained.

To calculate the viability of the localities across all scenarios and dates (including 2000) and as a means of visualizing the 'core localities', the totals from the models were calculated for each locality. Where the models return a consistently high predictive value (i.e. where there are high predictions across all scenarios and dates), localities exist in spaces that are predicted to have a relatively constant optimal bioclimatic environment. This provides a simple but powerful means of visualising the data for conservation planning and management. This could be extended by viewing the variability for each locality (to show those localities with highly changeable environments), and providing standard deviations for each locality across all scenarios and dates (data available on request).

Climate change scenarios (2020–2080) — an area analysis

For this analysis each scenario and date map was reclassified using the three thresholds calculated from the original year 2000 threshold percentages (68%, 95% and 100%) to give area-only predicted distribution (suitable bioclimatic space) (Figures 5 and 6). If an area was totally unsuitable in the year 2000, but became suitable in later scenarios, these areas were excluded in the re-classification. Thus, the prediction for 2000 provides a control for future migrations in our modelling (see Discussion – Modelling overview). This assumption was made because significant natural range extension, which requires effective dispersal and colonization, is highly improbable (see Discussion – Implications for wild populations of Arabica coffee).

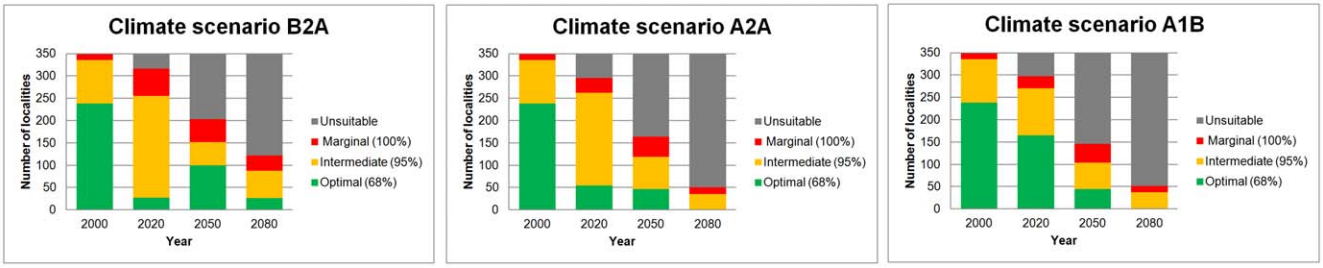


Figure 3. Locality analysis overview I. Predicted climate change outcomes for indigenous Arabica localities for the year interval 2000, 2020, 2050 and 2080. Stacked bar-charts based on Table 1. Green = optimal [bioclimatic] localities (68%); yellow = intermediate (suboptimal) [bioclimatic] localities (95%); red = marginal (extreme) [bioclimatic] localities (100%); grey = unsuitable bioclimatic localities.
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Results

Model of historical and present-day distribution

The potential present-day distribution of indigenous Arabica, as derived from MaxEnt [42–44], is shown in Figures 1 and 2, which include the locality records (1941 to 2006), representing the 713 data records, giving the 349 unique localities. For modelling purposes 197 data points were used, as only one data point was retained where points were clustered in a single cell (see Methods). AUC (area under the curve) is often used to evaluate species distribution models [50,59]. An AUC of 1 represents a perfect prediction and generally values of 0.5 or lower are no better than random, although there are fundamental problems when using AUC for validation [50]. We retrieved an AUC value of 0.99 for the predicted distribution across the whole of Africa, using all 197 sample points; removing spatial sorting bias (i.e. clustering), for the same region gave an AUC of 0.988. Finally, testing of the models after the removal of the spatial sorting bias, and using only the core region (as in Figure 5), gave an AUC value of 0.78. This was performed in order to test the models to the extreme, but not for the actual models used in the rest of the analyses (see Methods). Based on the outcome of the cross-validation tests [50] and expert visual assessment of the predicted distribution we believe that our MaxEnt models were very robust. The distribution includes south-western Ethiopia, south-eastern South Sudan (Boma Plateau) and northern Kenya (Mt. Marsabit). Within Ethiopia, the highest density of recorded presence is in the western-most part of the distribution, and there is a clear division between this area and the eastern side of the Great Rift Valley in the Bale Mountains, although two sites have been recorded between these two main areas of distribution (Figures 1 and 2). Very obvious outlying populations occur on the south-eastern part of Boma Plateau, near Towot (c. 6°6′N 34°26′E), and on Mt. Marsabit (2°16′N 37°58′E). Three localities have very low predictive scores, i.e. Mt. Marsabit (0.11) and two others (0.10 and 0.040; Figure 2B). The latter two localities are physically very close (9.8 and 6.7 km, respectively) to areas with higher predictions. The anomaly could be due to model sensitivity, or data inaccuracies, for example small areas of suitable bioclimatic space that are not picked up by the climate data modelling or the scale of the analyses, such as gallery forest (a forest growing along a watercourse in a region otherwise devoid of trees (or another vegetation type); in many cases gallery forest is less than 1 km wide). Given that these low scoring localities represent a small proportion of the total number of localities, and that the model fit is very strong, they hold little significance in terms of the overall modelling. In addition, even though the Mt. Marsabit locality is only marginally suitable for the occurrence of indigenous Arabica as a whole, there are smaller areas on the mountain that receive a slightly higher prediction than for the entire mountain area (data not shown).

The following BIOCLIM layers give the highest contributions to the model of predicted distribution: bio 4 (Temperature Seasonality); bio 10 (Mean Temperature of Warmest Quarter); bio 14 (Precipitation of Driest Month); and bio 8 (Mean Temperature of Wettest Quarter). Therefore, temperature, precipitation, and their relationship with seasonality, are the biggest drivers for the models, although it should be reiterated (see Methods) that these are not necessarily the actual environmental drivers for the occurrence of the species.

The threshold values (modelled scores given in parentheses) produced for the present day predictive models were 68% of localities (>0.564; 'optimal'), 95% (>0.392; 'intermediate'), and 100% (>0.0398; 'marginal'), as shown in Figure 2B. The optimal localities, i.e. those with 68% or higher, show an excellent visual fit with the actual recorded distribution (the 349 localities), and

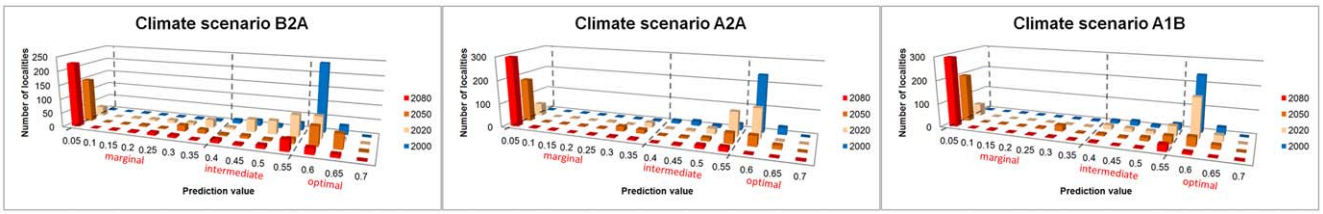


Figure 4. Locality analysis overview II. Predicted climate change outcomes for indigenous Arabica localities (349 in total) for the year intervals 2000, 2020, 2050 and 2080. Histograms for actual predicted values, under each scenario. Dashed line and red text indicate thresholds (68%, 95%, 100%, of the 2000 models). This figure provides finer-scale detail than Figure 3, including the subtle shifts around the thresholds that are evident in the locality analysis. For example in scenario B2A, in 2000 there are a high proportion of localities in optimum bioclimatic space (0.6 and 0.65), but by 2080 most of the localities are outside of all suitable bioclimatic space, with a small number of localities ('core localites') still occupying optimal bioclimatic space.
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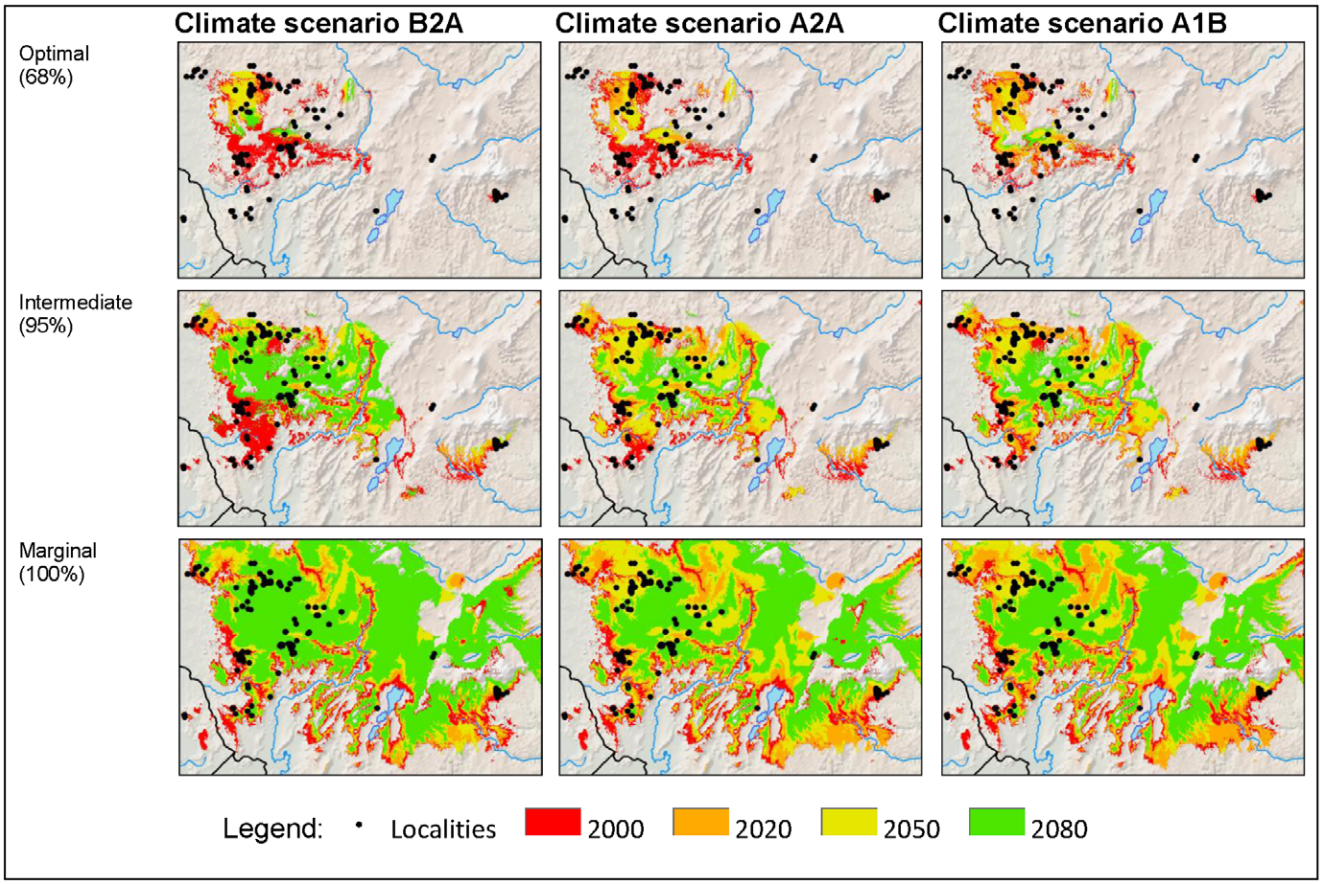


Figure 5. Area analysis maps. Predicted climate change outcomes for indigenous Arabica for the year intervals 2020, 2050 and 2080. Thresholds (of bioclimatic suitability) applied at 68% (optimal), 95% (intermediate) and 100% (marginal). Black dots show historical and present day localities.
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potential distribution based on specialist knowledge of the vegetation [56,57] (S. Demissew, pers. comm.; I. Friis, pers. comm.; T. Gole, pers. observ.).

Climate change scenarios (2020–2080) — a locality analysis

In the locality analysis the future modelled scenarios show a dramatic and profound decrease in the number of predicted bioclimatically suitable localities for indigenous Arabica (Table 1; Figures 3 and 4). In the B2A scenario (lower energy requirements, but with emissions greater than the minimum), which is the most conservative of the scenarios employed, of the 349 localities of 2000 the number is down to 122 by 2080, representing a reduction of 65% of all 349 localities across all thresholds (i.e. 68%, 95% and 100%; Table 1; Figures 3 and 4). At the 68% (optimal) threshold for the B2A scenario, only 26 localities remain suitable, of the original 238 localities from 2000; 212 localities (c. 90%) are outside the 68% threshold, i.e. occurring in either intermediate, marginal, or outside all, suitable bioclimatic localities by 2080. The projections for the localities under other scenarios are even more startling. For A2A (high energy requirements) and A1B (maximum energy requirements with balance across energy sources), by 2080 there are 298 and 299 localities (respectively) outside all thresholds (68%, 95%, 100%) which represents a reduction of 85% of all

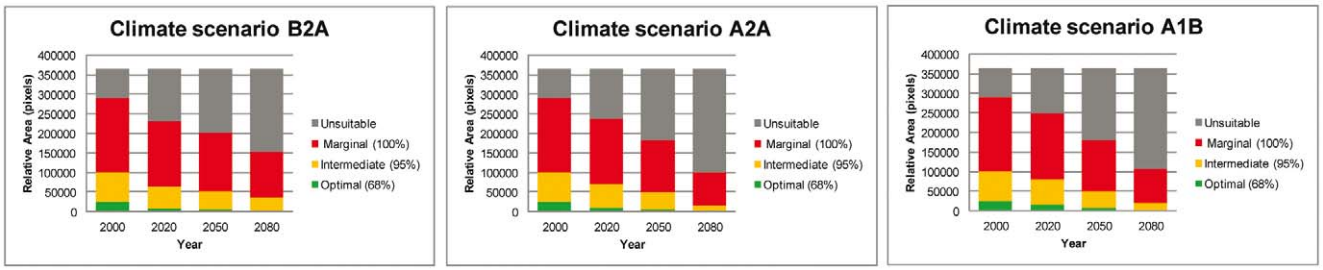


Figure 6. Area analysis overview. Predicted climate change outcomes for indigenous Arabica for the year intervals 2020, 2050 and 2080. Stacked bar-charts based on area analysis maps (Figure 5).
doi:10.1371/journal.pone.0047981.g006

Table 1. Number of (unique) localities in each threshold class for each climate change (emission) scenario and date.

	Present day	Climate scenario B2A			Climate scenario A2A			Climate scenario A1B		
	2000	2020	2050	2080	2020	2050	2080	2020	2050	2080
Optimal (68%)	238	27	100	26	54	46	1	165	44	1
Intermediate (95%)	97	228	52	62	208	73	34	105	60	36
Marginal (100%)	14	61	51	34	33	45	15	27	42	14
Unsuitable	0	33	146	227	54	185	299	52	203	298

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localities (Figure 3). At the 68% (optimal) threshold for scenarios A2A and A1B the model shows that by 2080 there will be only one locality for each scenario, representing an almost 100% loss of recorded bioclimatically suitable localities.

The locality analysis also shows that in the B2A scenario the number of optimal localities at the 68% threshold dramatically decreases for 2020, but then increases for 2050; and for A2A there is the same dramatic decrease and then a marginal reduction in 2050 (Figure 3). This is partly due to fluctuations around the 65% and 95% threshold values (i.e. around the 0.392 cut off), i.e. moving slightly either way increases/decreases the area of the histogram (see Figure 4 for further detail), and possibly because some localities become more bioclimatically suitable for a short period (e.g. c. 20 years).

Climate change scenarios (2020–2080) — an area analysis

As in the locality analysis, the area analysis is dominated by a significant reduction in predicted occurrence for Arabica until to 2080. The very inclusive threshold of 100% (marginal, and all other thresholds), where all present day localities would be considered as bioclimatic suitable, even those with very low original prediction values (e.g. 0.0398), still show a 38%, 56% and 55% reduction across all emission scenarios (i.e. B2A, A2A, A1B, respectively). Even under the 95% (intermediate) threshold the A2A and A1B and B2A scenarios show substantial reductions in the distribution area for Arabica, at 57%, 79%, and 75%, respectively (Figures 5 and 6). The prediction under the B2A scenario at the 68% (optimal) threshold is a c. 90% reduction. For A2A and A1B, again with the 68% (optimal) threshold, there is an almost 100% reduction (Figure 6). The area analysis also shows a general northward concentration through time (Figure 5), due to the modelled occurrence of newly available suitable bioclimatic space.

Discussion

Modelling overview

Our study shows that modelling driven by locality data of sufficient quantity and quality (i.e. 349 unique localities, each accurate to 30 arc seconds resolution (c. 1 km diameter) or less), and conducted on a regional scale, drives robust models for Arabica. This approach appears to outperform environmental envelope methods based on the climatic thresholds of a limited number of variables [14,15,36], e.g. mean temperature and mean rainfall. Our predictive present-day distribution model for Arabica is assumed to be accurate and robust (Figures 1 and 2), due the strength of the distribution model and robust agreement with both ground-truthing and visual assessment using satellite imagery (using Google Earth (Version 5; ©2010 Google). We infer that Mt. Marsabit in northern Kenya is probably not part of the natural range of Arabica, due to the low prediction scores for this locality. This assumption supports the available molecular data, which shows that samples (two in total) from Mt. Marsabit fall within a broad selection of Arabica cultivars and are not aligned with spontaneous populations from Ethiopia [23]. Further work on this outlying locality is required, including fieldwork in those areas that receive slightly higher predictions (see Results – Model of historical and present-day distribution.)

Future distribution predictions for indigenous Arabica based on future scenarios (B2A, A2A, A1B) and the HadCM3 climate model [52,53] for the time intervals 2020 (an average of the years 2010–2029), 2050 (2040–2059), and 2080 (2070–2089), were analysed using a locality analysis and an area analysis. Both analyses performed well but overall the locality analysis has greater meaning and more practical applications: the data (actual localities based on *in situ* observations across the distribution range) can be tracked through time, from 2020 to 2080. Generally, the locality analysis also requires fewer assumptions. In the area analysis, the 68% (optimal) threshold is likely to be very exclusive. For example, if in 2050 a pixel falls into the 95% (intermediate) threshold from the 68% threshold it would stay within the former threshold in subsequent dates. This same exclusivity is present in the 95% (intermediate) threshold, but to a lesser degree; it does not apply to the 100% (marginal) threshold. The exclusivity of the area analysis means that more caution is required in the interpretation of the predictions. Moreover, in the area analysis the actual area of change is not entirely meaningful, even when surface area values are provided, because of the clipping of the study area and other assumptions made in the modelling. What is important is the relative change across time and scenarios, i.e. the universal reduction of available suitable bioclimatic space until 2080 (Figure 6).

Our modelling approach for Arabica is not constrained by climatic optima, as used in environmental envelope methods [14,15,36], and by default encompasses the broader bioclimatic ranges encountered in wild populations, which have a much higher genetic diversity and a greater physiologically variability compared to cultivated Arabica [28,29]. It is also clear that there is a dichotomy between modelling the success of plantations, which is largely measured by yield and beverage quality [3,5] and the health and survival of the species, which in stressed environments may exceed the given climatic optima required for successful production of Arabica coffee beans. For example, temperatures above 28–30°C are likely to reduce flower bud formation (and thus fruit production) in indigenous Arabica populations but may not significantly influence morbidity or mortality, at least in the short term (A.Davis and T.Gole, pers. observ.).

Bioclimatic suitability for indigenous Arabica is not a simple association with a linear temperature change but is heavily

influenced by seasonality (as identified above). This issue is further complicated by two other factors. Firstly, the present-day prediction (the year 2000) is actually an accumulation of collection dates from 1941–2006 and secondly, the climate data used for the modelling for the year 2000 is accumulated from weather station data from the 1961s to 1990 [49]. The consequence of these considerations is that the prediction for the present-day (2000) distribution of wild Arabica (Figures 1 and 2) could be overly inclusive, that is, the area predicted could be larger than it actually is. However, examination of suitable vegetation and optimal bioclimatic area, based on field observation (S. Demissew, pers. comm.; I. Friis, pers. comm.; T. Gole and A.Davis, pers. observ.) and inspection of satellite imagery shows that this is not the case: the predicted distribution for indigenous Arabica is concurrent with known populations and areas that are highly suitable for the occurrence of this species.

Implications for wild populations of Arabica coffee

Our modelling shows a profoundly negative trend for the future distribution of indigenous Arabica coffee under the influence of accelerated global climate change. In our locality analysis the most favourable (and most conservative) outcome (scenario B2A; all thresholds) would be a c. 65% reduction in the number of bioclimatically suitable localities, and at worst (scenarios A2A, A1B; 68% threshold) an almost 100% reduction, by the year 2080 (Table 1; Figures 3 and 4). Part of the strength of this analysis is that the locality data used for the modelling covers a high proportion of suitable bioclimatic space in remaining areas of Moist Evergreen Afromontane Forest and Transitional Rain Forest [56], i.e. the vegetation types where Arabica exists. Even if new localities for Arabica are recorded, these are likely to represent a small proportion of those already known, based on the few remaining suitable areas for which we do not have occurrence records. New records are unlikely to influence the modelling, as performed here, to any considerable extent: the predicted percentage loss is unlikely to change dramatically. It should reiterated that our modelling does not incorporate vegetation, due to the absence of a suitable atlas of remaining vegetation for the study area [56]. The assumptions we have made, post modelling, are based on intact vegetation, and on the highly unrealistic premise that there will be negligible human generated land-use change until 2080. Therefore, all of our future predictions should be considered as moderate, at the very least.

In our area analysis, the most favourable outcome (scenario B2A; 100% (marginal) and including all other thresholds) would be a 38% reduction in suitable bioclimatic space, and the least favourable (scenarios A2A, A1B; 68% (optimal) threshold) a 90% reduction, by 2080. The area analysis predicts a general northward concentration through time, i.e. an increase in suitable bioclimatic space in the northern part of the distribution, although the likelihood of migration and establishment by Arabica is assumed to be extremely limited based on insubstantial dispersal and colonization ability, especially in stressed environments. Arabica has a relatively long generation time: even in cultivation it requires a minimum of three to four years to produce fruit and at least five to eight years to reach maximum reproductive potential [60]. Re-colonization potential into suitable areas, let alone marginally suitable ones, is restricted even at the simplest level (e.g. without considering pollinator and dispersal availability, deforestation, loss of niches to more aggressive colonizers). At best re-colonization will be limited and localized, especially with increasing distance from the parent population. Moreover, it is doubtful that suitable vegetation types will have established within the time-frame required. Totally unsuitable habitat (e.g. *Combretum-Terminalia* Woodland and Wooded Grassland) is highly unlikely to become suitable habitat (Moist Evergreen Afromontane Forest, and Transitional Rain Forest [56]) over an 80 year time period. In our methodology we have imposed a zero rate for migration, based on a neutral colonization rate, an assumption that is supported by studies of other forest dwelling plants, where migration rates to newly formed areas of suitable vegetation are given as either nearly impossible [61–63] or severely restricted [64]. Birds are probably the main dispersal agents of coffee species in Africa, but modelling indicates that the avian fauna of tropical regions will be reduced in extent and diversity throughout the century [65], and this is likely to reduce the number of possible dispersal events for Arabica. A further compounding factor is that the present coverage of Moist Evergreen Afromontane Forest and Transitional Rain Forest of Ethiopia, the vegetation housing wild populations of Arabica in Ethiopia and South Sudan, is now fragmented, and often degraded [56]. Fragmentation reduces the progress and success of migration for many forest species, and would hinder the establishment of new areas corresponding to Moist Evergreen Afromontane Forest and Transitional Rain Forest vegetation types. Managed relocation of Arabica individuals or even populations by human effort is conceivable, although as with any other form of dispersal a suitable habitat would have to be available during this process and these may be limited (see above) and localized.

In both the locality and area analysis numerous populations outside the main area of distribution (i.e. SW Ethiopia) are predicted to occur outside of all suitable bioclimatic space for Arabica by 2080 (Figures 4 and 5). Even by 2020, some of the populations on the outer edges of the main SW Ethiopia distribution area, several in the Bale Mountains (southern central Ethiopia), and all populations on the Boma Plateau in South Sudan and Mt Marsabit in northern Kenya, will be occurring in unsuitable bioclimatic space. Bioclimatic unsuitability would place populations in high peril, leading to severe stress and a high risk of extinction in the short-term. Ground-truthing would be necessary to test the likelihood and scaling of predictions in terms of population persistence and survival. A recent survey (April 2012) on the Boma Plateau (A.Davis, T. Schilling, S.Krishnan, pers. observ.) is consistent with our modelling. Observations made in the most suitable bioclimatic space on the Boma Plateau indicated that Arabica populations are stressed (loss of aged individuals, meagre population density, minimal seedling recruitment, low-ratio of flower bud development) compared to 70 years ago [37]; subcanopy ambient air temperatures recorded at the end of the dry season (9–12 April 2012), during the middle of the day, were between 28–30°. Some of this stress has no doubt been caused by human intervention, and probably foremost among these would be the burning of the surrounding *Combretum-Terminalia* Woodland and Wooded Grassland for grazing, which increases the temperature and lowers the humidity inside the contiguous Transitional Rain Forest. In some places the fire had encroached into the margins of the forest, as demonstrated by the presence of recent charcoal layers detected directly underneath the forest leaf-litter, and this may be expected anywhere where forest and fire-managed grassland co-exist.

There could be a buffer influence for wild populations of Arabica, because the forest micro-environment itself is not included in recorded climate data and therefore not modelled. That is, certain variables such as the mean temperature(s) will be lower inside the forest than in exposed areas in the same general bioclimatic space. In addition, the long generation time of Arabica (c. 50 years, and perhaps up to 100 years [4]) will mean that even if reproduction, dispersal and colonization are reduced, or neutral-

ized, individual trees may persist for some time. However, observations of Arabica populations in South Sudan show that in degraded forest with good canopy cover, at the end of dry season, the difference in ambient air temperature between forest and non forest may only differ by 1°C or less; and on comparing anecdotal accounts with historical records [37] it seems that the mature trees have fared less favourably in these stressed environments compared to juveniles ones (A.Davis, T.Schilling, S.Krishnan, pers. observ.). Moreover, the influences of climate change on the cornerstone species of the Moist Evergreen Afromontane Forest, and Transitional Rain Forest vegetation types are unknown, and thus the outcome for the forest itself cannot yet be predicted.

The impact of multiple compounding influences acting simultaneously on an organism and its associated biota under accelerated climate change would be very difficult to model, but the individual and combined consequence are likely to be negative. The single most important compounding influence for Arabica is almost certainly habitat degradation and loss due to forest modification and clearance, especially for agriculture [4,17]. This would include the vegetation surrounding and buffering the Moist Evergreen Afromontane Forest and Transitional Rain Forest, i.e. mostly *Combretum-Terminalia* Woodland and Wooded Grassland but also Dry Evergreen Afromontane Forest [56]. In particular, *Combretum-Terminalia* Woodland and Wooded Grassland is burnt to produce grazing lands [56] and this in turn can raise temperatures and decrease humidity within Moist Evergreen Afromontane Forest and Transitional Rain Forest, and especially in smaller forest fragments.

Pests and diseases are also likely to be important. A study on the East African Kihansi coffee (*C. kihansiensis* A.P. Davis & Mvungi) [66], a species entirely restricted to Kihansi Gorge in Tanzania, provides us with a good example of how coffee species are influenced by pests under accelerated climate change. The underground diversion of the Kihansi River for hydropower production was completed in 1999. The mean temperature and relative humidity at this site in 1997 were 21.23°C and 76.64%, respectively; six years after dam construction these had changed to 24.08°C (+2.84°C) and 68.76% (−7.88%) [67]. These changes coincided with the appearance and chronic spread of a parasitic infestation, apparently correlated to the change in local climate, which has seriously undermined the growth and reproductive potential of this coffee species, with severe consequences for the long-term survival of the species [67]. For Arabica, the coffee berry borer (*Hypothenemus hampei* (Ferrari) [Coleoptera]) poses a significant compounding threat to indigenous populations and plantations. Coffee berry borer, the most important biotic constraint for commercial coffee bean yield worldwide, was unable to complete a single generation per year in SW Ethiopia (Jimma) before 1984, due to low temperatures, but thereafter, because of rising temperatures in the area, it was predicted that the pest would be able to complete one or two generations per year/coffee season [13,68]. These predictions have been confirmed by an independent study, which shows that the coffee berry borer is now widespread in SW Ethiopia [69]; before 1984 it was absent. Overall, the climatic suitability for coffee berry borer is predicted to increase in southwest Ethiopia [13].

Implications for cultivated Arabica coffee in Ethiopia and world-wide

The outcome of climate change for Arabica cultivation in Ethiopia, the only coffee grown in the country, is also assumed to be profoundly negative, as natural populations, forest coffee (semi-domesticated) and even plantations occur in the same general bioclimatic space as indigenous Arabica. Forest coffee and semi-forest coffee production systems account for c. 25% of total coffee production in Ethiopia [4]. Production is likely to decrease significantly in certain areas, and especially in locations that are presently marginally suitable for coffee production. Most coffee cultivation in Ethiopia is shade-grown and without irrigation, the latter being a practice that can significantly influence the productivity and survival of Arabica in suboptimal growing areas [60]. Unlike native forests, however, there may be greater short term incentives to employ mitigation measures, such as irrigation, particularly at the lower scales involved (e.g. at farm-level).

Our results provide independent validation that Arabica is a climate sensitive species, supporting data on recorded climate optima [3–6], results based on environmental envelope methodologies [14,15], and anecdotal information from coffee farmers. The logical conclusion is that Arabica coffee production is, and will continue to be, strongly influenced by accelerated climate change, and that in most cases the outcome will be negative for the coffee industry. Optimum cultivation requirements are likely to become increasingly difficult to achieve in many pre-existing coffee growing areas, leading to a reduction in productivity, increased and intensified management (e.g. the use of irrigation), and crop failure (some areas becoming unsuitable for Arabica cultivation). Detailed modelling of Arabica cultivation is required, on local and regional scales, in order to inform famers and decision makers as to the requirements for future-proofing the sustainability of their crop. The methodology used here could be adapted for coffee plantations on a regional scale, by substituting the location of plantations for indigenous populations, and by applying a modified threshold approach based on the parameters encountered and employed in cultivation.

Conservation of wild Arabica coffee

Unlike cultivated Arabica coffee, the distribution of indigenous populations is controlled almost entirely by natural, biotic parameters, even though these factors are influenced by anthropogenic actions. Assisted migration of wild Arabica could be suggested as a possible means of mitigation, but in reality this option is laden with constraints. Not least are the short-term financial implications associated with resourcing a medium- to long-term and diffuse (i.e. involving multiple populations) action of assisted migration. Re-locating coffee plantations is likely to bring economic benefits within a realistic time frame; the assisted migration of natural populations of Arabica coffee is not.

What we have shown here is that under a range of emission scenarios some populations of Arabica (occurring in optimal bioclimatic space) might be able to resist climate change until 2080, at least in the absence of severely negative influences (e.g. deforestation). We define these populations here as 'core localities' (Figure 7; high prediction totals across all scenarios) and suggest that they should be assessed as candidates for the long-term *in situ* conservation of Arabica in the face of accelerated climate change. Examination of the main protected areas of Ethiopia shows that some of the 'core localities' already fall within those established protected areas [70] and have a reasonable to good degree of protection (e.g. national parks and UNESCO biosphere reserves), although many do not (Figure 7). Where there is a specific objective for the *in situ* conservation of indigenous populations of Arabica, such as the Yayu and Kafa Biosphere Reserves (Figure 7), the 'core localities' falling closely outside these protected areas should be assessed and, if suitable, be incorporated into protected area delimitation and long-term management. Other 'core localities' should be assessed on a case-by-case basis. Conversely, those localities identified as marginally suitable for Arabica in the

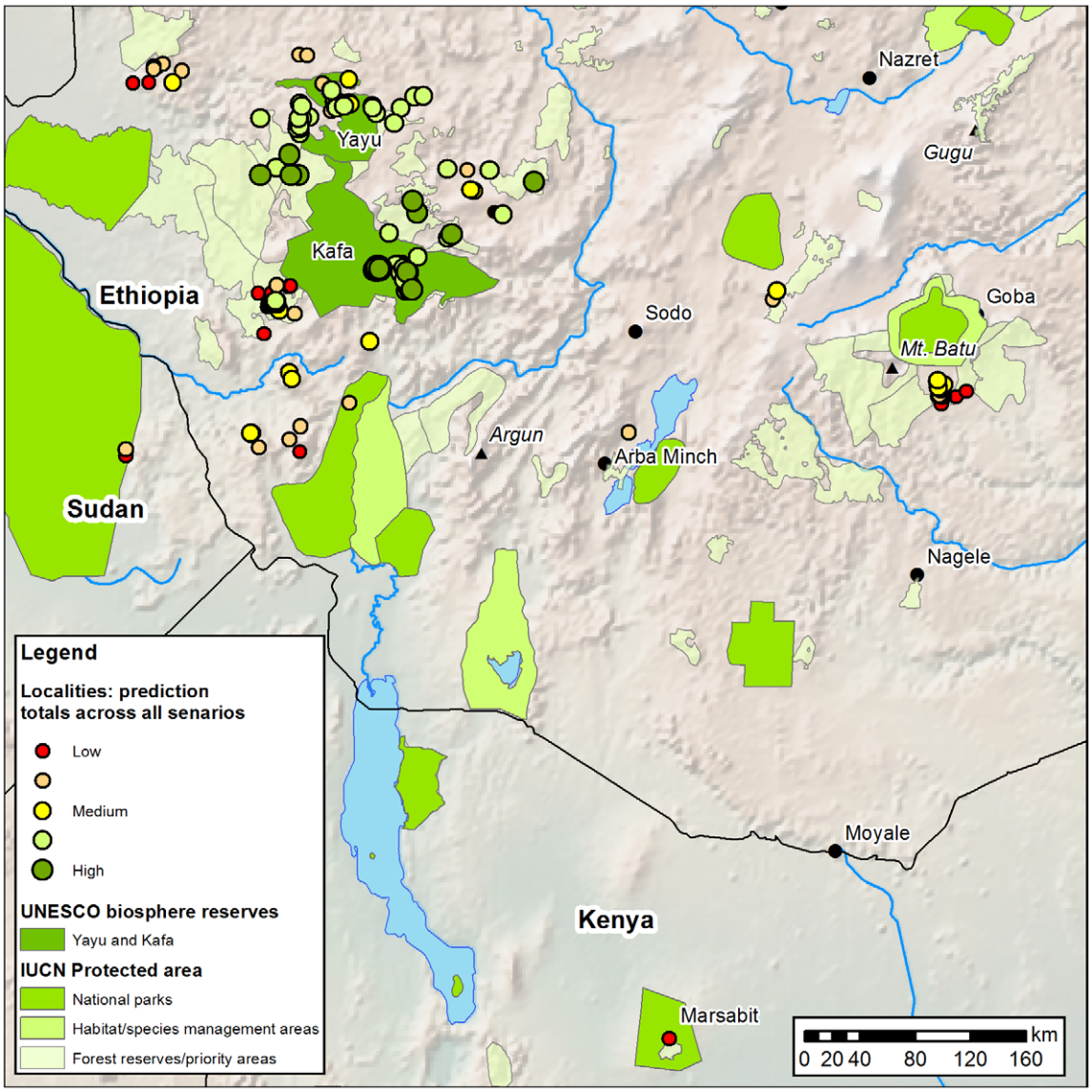


Figure 7. Locality analysis predictions superimposed on main protected areas in the study region. Point size and colour represent the total predicted score for each locality across all scenarios and time intervals (until 2080). Large dots (high score) represent 'core localities', i.e. those that predicted to withstand climate change until at least 2080. See internal legend for further details. Protected area data from [70]. Dedicated coffee reserves: Yayu = Yayu Coffee Forest UNESCO MAN Biosphere Reserve (http://www.unesco.org/mabdb/br/brdir/directory/biores.asp?code = ETH+02&mode = all. Accessed 2012 May 10), included within the Yayu National Forest Priority Area (NFPA) (http://www.ecff.org.et/component/content/article/10-yayu/6-yayu-coffee-forest-biosphere-reserve.html. Accessed 2012 May 10); Kafa = Kafa Coffee Biosphere Reserve UNESCO Biosphere Reserve (http://www.kafa-biosphere.com/. Accessed 2012 May 10). Note. Controlled Hunting Areas not shown.
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present-day (Figure 2B) and unsuitable in the short- to medium-term (Figure 7), are suggested as priorities for *ex situ* conservation.

Closely associated with the need to identify populations for conservation will be the requirement to assess the genetic variation of indigenous Arabica, and particularly in relation to their bioclimatic profiles (either modelled or directly measured), and physiological response to climate change. For example, genetic assessment and monitoring of populations either side of the Great Rift Valley could be rewarding, as they are already known to possess different bioclimatic tolerances and other potentially valuable characteristics [30,31]. These two main areas of distribution receive the bulk of their rainfall from different directions and at different times of the year [57]. In undertaking such work it might be possible to identify local variants that have improved thermal and/or drought tolerance, which can be used in the development of cultivated Arabica stock.

Next steps for present and future distribution modelling of indigenous Arabica coffee

Despite the limitations of assessing the impacts of climate change using the single-species approach via bioclimatic modelling [32,33], and in the absence of more detailed ecological and physiological data [34,35], this study has firmly established a baseline for assessing the consequences of climate change for indigenous Arabica coffee. It is important to bear in mind that we have used here and single climate model (HadCM3), with one niche modelling method (MaxEnt). Whilst the quantitative results

could be quite different using other climate and niche models, we believe that the overall projections and trends will be similar with the present resources at hand. For more precise modelling of future distribution trends for Arabica, mapping and modelling work should incorporate actual (remaining) vegetation, as opposed to a potential vegetation [56], although these data are not presently available. These mapping data would be used to 'clip' suitable remaining habitat for Arabica from the models, and provide more accurate estimates for loss of suitable bioclimatic space. More detailed ecological data (subcanopy temperatures, soil/water balance, soil type, humidity, evapotranspiration) is also required. Collecting these data across the entire natural range of Arabica is possible, although a focused approach using selected sites is more realistic. On-the-ground monitoring of stress (e.g. seedling recruitment, flower bud and fruit development, leaf yellowing, leaf drop, and pests and disease) for selected populations (as identified here) over suitable time intervals, will be necessary to fully ground-truth the validity and scaling (e.g. categorization of bioclimatic scoring in terms of morbidity and mortality) of our modelling. There is also a requirement to conduct surveys in areas that have high and low predictions for the presence of Arabica (and suitable remaining vegetation) but presently lacking records of occurrence; ideally presence and absence of populations would be accurately recorded in a systematic manner. Finally, as new climate change models are developed, and existing ones refined, there will be a need to re-analyze the existing data, with greater temporal (e.g. 10 year intervals) and spatial resolution, possibly using some sort of consensus approach.

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Author Contributions

Conceived and designed the experiments: APD TWG SB JM. Performed the experiments: APD TWG SB JM. Analyzed the data: JM SB. Contributed reagents/materials/analysis tools: APD TWG SB JM. Wrote the paper: APD JM. Designed methodolgy for area analysis: JM.

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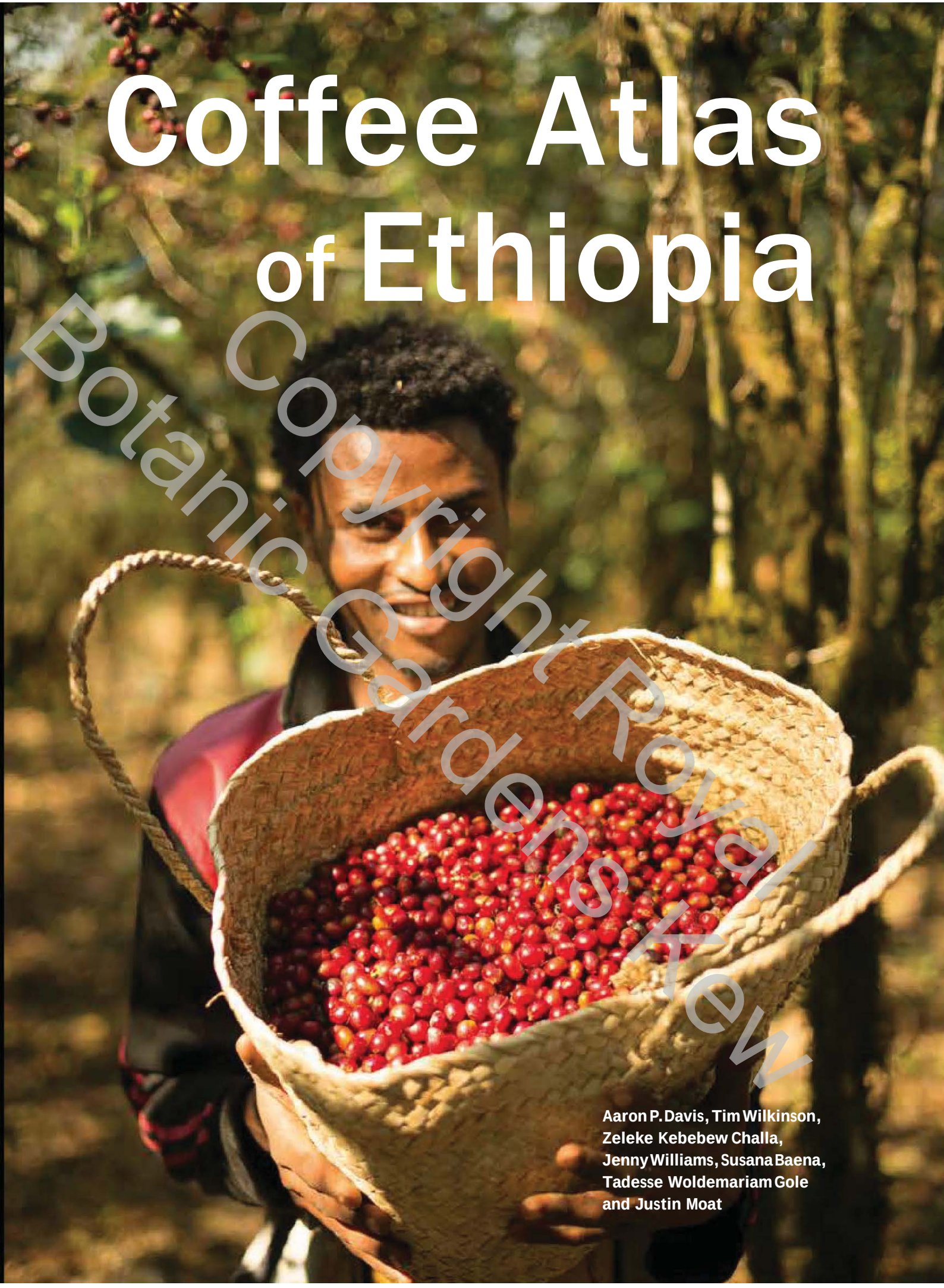
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Coffee Atlas of Ethiopia



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Tigray (northern Ethiopia)

Image: Jenny Williams


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1. Introduction

When we talk about Ethiopia and coffee, we are referring to one species only: Arabica coffee (*Coffea arabica*). In its wild state Arabica coffee is a forest plant restricted to the highlands of Ethiopia and neighbouring South Sudan[1]. It has been used in Ethiopia as a food and beverage for many hundreds, if not thousands, of years. Early use was no doubt restricted to gathering fruits from wild forests, with semi-domestication probably coming soon afterwards. Today, Arabica coffee provides a quarter of Ethiopia's export earnings[2] and livelihoods for around 15 million coffee farmers[2–4]. For many of these farmers, coffee is their single most important source of income. Around 50% of the coffee produced within Ethiopia stays within the country, for consumption by Ethiopians. Indeed, coffee drinking is a part of everyday life in Ethiopia, and a key component of Ethiopian culture. As well as the well-known Ethiopian coffee ceremony, coffee is used at major events such as marriages and births, at regionally specific celebrations, and as a medium to build and sustain relationships between family, friends and the community. In Ethiopia coffee is almost universally known as *buna* or *bunna*.

Ethiopian coffee is world-renowned for its broad range of diverse and unique flavour profiles (smell and taste). There are two main reasons for this. First, Ethiopia is the world's main storehouse of genetic diversity for Arabica coffee, and this diversity is manifest in the chemicals that produce flavour. Second, Ethiopia has a complex climate and landscape, resulting in regional and local differences across the coffee-growing landscape. The geographical location associated with the various flavour profiles are often referred to as 'origins', a term used similarly to *terroir* in the wine industry. Included amongst these origins are the well-known coffees of Harar, Limu, Nekemte, Sidamo and Yirgacheffe, but there are numerous lesser-known origins, which are also unique and distinct. The wide spectrum of flavour profiles adds a unique element to Ethiopian coffee, and makes it especially well-suited to the demands of the high-quality 'speciality' coffee sector. The vast majority of Ethiopian coffee is organic, by default, as most production systems use no synthetic fertilisers, herbicides or pesticides. In addition, because of the intimate association with natural forests, Ethiopian coffee usually has substantial environmental benefits, as outlined below.

Ethiopian coffee is mainly grown under the shade of trees (shade or forest coffee), either within forest or forest-like environments or in farming systems that incorporate specific shade plants, usually indigenous (native) trees or sometimes fruit trees and other crop plants.

Forest is important for coffee because it provides the right conditions for healthy plant growth and successful cropping. It also provides key environmental services, including nutrient recycling, soil preservation, watershed protection, pollination services, temperature buffering, shelter from wind and heavy rainfall, and carbon storage. Ethiopian coffee forests also provide a home for a diverse assemblage of plants and animals, and are thus important for biodiversity preservation.

It is evident, then, that Ethiopian coffee production has many positive attributes, for the consumer and the environment.

Overview

In the *Coffee Atlas of Ethiopia*, our aim is to provide a detailed mapping resource for both farmed and wild Arabica coffee. The Atlas text provides details of the methods used for the production of the maps, as well as background information on geography, the use and consumption of coffee, the botany of the Arabica coffee plant, the coffee-growing climate and agroecology, coffee farming and processing, the coffee-growing areas, and scope and use of the Atlas. At the end of the Atlas there is a gazetteer (geographical name index), to help the user find the geo-political zones, features of the coffee landscape (e.g. key coffee origins, coffee towns and coffee delivery centres), regional capitals, airports, protected areas (e.g. wildlife reserves), major lakes, summits, and towns (settlements).

The maps in the *Coffee Atlas of Ethiopia* show where Arabica coffee is farmed, and could be farmed, and where it is found naturally (i.e. in its wild state). They also show the places where shade coffee is produced, in forest and forest-like environments (such as forest coffee and agroforestry). Coffee garden areas, where either little or no shade is employed, are depicted with a coffee bean symbol. Humid forest (mostly evergreen and rainforest-like) but with no present-day suitability for coffee is also mapped in the Atlas.



LEFT
Drying washed (parchment) coffee on a raised bed (Yayu, south-west Ethiopia)
Image: Alan Schaller (courtesy of Union Coffee)

RIGHT
Travelling across the drylands of the Rift Valley
Image: Jenny Williams

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2. Cartographic methods

The coffee map layers were produced by combining high resolution satellite data (for forest cover) and niche modelling (for coffee suitability). Information on the use of the Atlas is found in Chapter 12 (Scope and use of Atlas).

To publish only the coffee areas and forest without any landscape features would render the Atlas near useless, as readers would find it difficult to determine their location. To make the map navigable and to give the reader context, we have over and under laid our coffee mapping data with infrastructure (e.g. roads and towns), boundaries, elevation data, rivers, lakes and protected areas (e.g. National Parks), and added graticules (the horizontal and vertical lines) for longitude and latitude on each Atlas page. The mapping layers used in the Atlas, and their origins, are given below:

Data set	Data origin
Main coffee areas	Royal Botanic Gardens, Kew – SCIP project
Coffee forest	Royal Botanic Gardens, Kew – SCIP project
Other forest	Royal Botanic Gardens, Kew – SCIP project
Other forest (north)	Global Forest Watch
Coffee niche	Royal Botanic Gardens, Kew – SCIP project
Coffee gardens	Royal Botanic Gardens, Kew – SCIP project
Coffee towns	Royal Botanic Gardens, Kew – SCIP project
Coffee localities	Royal Botanic Gardens, Kew – SCIP project
Protected areas	Environment & Coffee Forest Forum (ECFF)
Elevation data	SRTM 90 m Digital Elevation Database v. 4.1 (from CGIARCSI)
Towns	EthioGIS & Royal Botanic Gardens, Kew – SCIP project
Mountains	GEOnet Names Server
Airports	EthioGIS & Royal Botanic Gardens, Kew – SCIP project
Transport	EthioGIS & Royal Botanic Gardens, Kew – SCIP project
Borders	EthioGIS
Drainage and water bodies	EthioGIS & Royal Botanic Gardens, Kew – SCIP project

It should be noted that some of the data are based on outdated information, but this was the best we could access during the course of the project. Additional mapping data for towns, airports and transport (i.e. roads) was collected on-the-ground (during the SCIP project), and from satellite images (including review in Google Earth). The mapping data presented here should not be relied upon for detailed road navigation, and should be used with the following disclaimer in mind. *The information in this Atlas was derived from multi digital databases. A great deal of effort has been taken in the creation of this Atlas, but inevitably, omissions, or positional accuracy will occur. There are no warranties, expressed or implied, including the warranty of merchantability or fitness for a particular purpose, accompanying this product.* Notification of any errors would be appreciated.

The names of settlements (e.g. towns) and other mapped items are subject to change and regional variation. In addition, the names and geographical delimitations we have used for zones (see Chapter 12. Scope and use of Atlas) are unlikely to follow the most recent nomenclature and geographical boundaries precisely.

Colour scheme

Producing a colour scheme for the Atlas was a difficult task, as it needed to be readable and printable, to represent the features being mapped adequately, and to be aesthetically pleasing. We also wanted to account for readers who are colour blind. The colours chosen for the Atlas relate to the environmental suitability (the niche) for coffee, suitable forest cover, and other humid forest cover (presently not suitable for coffee). Please see Chapter 12 (Scope and use of Atlas), for further details.

These colours should allow the majority of colour blind readers (at least those with red-green colour blindness) to interpret the maps. To assist in this process we used colorbrewer2 (**http://colorbrewer2.org/**) to refine our colour representation for computer screens and for printing. A coffee bean symbol is used to represent the general distribution of coffee garden areas but not their precise locations, although the distribution is based on detailed computer modelling. Finally we added a very lightly hued hill-shaded elevation layer to the background, to give the impression of topology. A topological map is provided in Figure 8; see page 61 for details.

Projection

To represent the land surface and distances as accurately as possible we used the same projection and datum for all of our mapping. Most of the data used were either in geographic coordinates (latitude and longitude) using World Geodetic System 1984 (WGS84) or Universal Transverse Mercator (UTM) projection, Zone 37N.

The national projection used for Ethiopia is UTM Zone 37 N using the Adindan datum. On testing the Adindan and WGS84 datum for on-the-ground difference, the maximum difference was 150 m, which is well below our mapping scale of 1:500,000. The Adindan and WGS84 datum are more or less interchangeable at the scale of this Atlas. The Atlas maps incorporate graticules for latitude and longitude in degrees and minutes. A summary of the projection used is given below:

Projection: Transverse Mercator
False easting: 500000
False northing: 0.0
Central meridian: 39.0
Scale factor: 0.9996
Latitude of origin: 0.0
Linear unit: Meter 1.0
Datum: WGS 1984

LEFT
Landsat 8 false colour composite satellite image, for West Arsi and a part of the Sidamo coffee area, south-east of Hawassa. Bright red represents forest and forest-like vegetation; lighter colours mainly represent cultivated and pastoral activities. See Atlas map page 12.
Image: Landsat 8. United States Geological Survey (2015).

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Format

We have divided the Atlas into 40 A4 pages and have extended the mapping beyond the coffee areas into regions that might be of more general interest to the reader. An index map is presented on Atlas map page 1. To help with navigation, the adjacent pages of the Atlas are given in purple triangles at the margin of the page. The key is presented on the index map and, where space permits, on additional map pages.

Mapping of the humid (coffee) forest

A coffee forest map of humid forest cover (Transitional rain forest (TRF) and Moist evergreen Afromontane forest (MAF))[5] was produced from 38 Landsat 8 satellite images[6], covering 24 Landsat scenes (2013–14). The Landsat imagery was atmospherically corrected[7] and cloud masked[8] to generate a cloud-free composite image. From this image a Normalised Difference Vegetation Index (NDVI) layer was produced[9] and two thresholds derived to identify TRF and MAF. Forest cover (type and extent) was reviewed using expert assessment, including ground truthing during extensive fieldwork[10].

Mapping of coffee suitability

The coffee suitability (niche) mapping layers were produced using species distribution modelling (SDM), in conjunction with bioclimatic variables (BIOCLIM[11]). We trialled and examined all 19 BIOCLIM variables statistically, and used expert review to make sure the variables made ecological sense for Arabica coffee. Using a refined selection of BIOCLIM variables, we analysed the data using six modelling methods to produce a final ensemble model[12] for each side of the Rift Valley (east and west). We critically examined each model, keeping in mind the environmental and physiological requirements of Arabica coffee[10].

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Humid (coffee) forest (Bonga, south-west Ethiopia)

Image: Jenny Williams

3. Geographical overview

Location and size

Ethiopia is located in north-east Africa, in the Horn of Africa, north of the equator. The country extends from latitude 3°36'N to 14°53'N and longitude 33°00'E to 48°00'E, and is approximately 1,200 km from north to south, and 1,600 km from east to west, at the widest points. The land surface area is 1,104,300 km^2, making it the 10th largest country in Africa and the 27th largest country in the world by area. In comparison to other major coffee-producing countries, it is almost eight times smaller than Brazil (8,515,770 km^2), three times bigger than Vietnam (330,967 km^2), and about the same size as Colombia (1,141,749 km^2). Ethiopia is land-locked and bordered (clockwise, from the north) by Eritrea, Djibouti, Somalia, Kenya, South Sudan and Sudan.

Topology and elevation

Ethiopia is a country of great topological contrast. The western and central part of the country is dominated by the high plateau and mountains of the Ethiopian Highlands. The eastern part of the country is mostly dry lowland and semi-desert (Figure 5, page 28). The Ethiopian Highlands range from approximately 1,000 m to 3,000 m, with numerous peaks above 4,000 m, including Ras Dejen (Ras Dashen) (c. 4,600 m) one of several high peaks in the Simien Mountains (in the north), and Mount Tulu Dimtu (4,389 m) on the Sanetti Plateau in the Bale Mountains (in the south). There are many other high peaks, including those above 4,000 m, which fall outside the Simien and Bale Mountains. The Ethiopian Highlands are divided by the Great Rift Valley, which runs roughly north-south; in the north-east the highlands are separated by the Afar lowlands. Elsewhere the Ethiopian Highlands are surrounded by lowland areas, except in the far north of the country where it borders with Eritrea (Figure 8, page 61). The highest point in Ethiopia is the peak of Ras Dejen (c. 4,600 m), and the lowest is in the Danakil Depression (125 m below sea level) of the Afar lowlands.

Major rivers and lakes

Ethiopia has numerous major rivers, which are important nationally and for bordering countries. Many of the larger rivers, such as the Blue Nile, are in deep valleys and form key features of the landscape. The main rivers are described briefly (below), anti-clockwise from the northernmost river first (Figure 5, page 28). The Tekezé River rises in the highlands of northern Ethiopia, east of Lake Tana, and flows north and then north-west to run along the border with Eritrea to Sudan, where it joins the Atbara River, a tributary of the Nile. The Blue Nile (known as the Abbay River in Ethiopia) starts at Lake Tana (see Atlas map page 34), and flows due south and then westward to Sudan. It meets the White Nile at Khartoum (Sudan), and together these rivers represent the two major tributaries of the Nile. The Baro River rises in the Ethiopian Highlands in south-western Ethiopia, and flows west through the Gambella Region (and through the city of Gambela; Atlas map page 16) to South Sudan, where it joins the Pibor River. To the south of the Baro is the Gilo River (Atlas map page 8), another major river of the Gambella Region, which originates in the southern part of the Ethiopian Highlands, from where it flows westwards to also join the Pibor on the border with South Sudan; the Pibor is a tributary of the White Nile. The Omo River is the principal river of southern Ethiopia, and rises in the central Ethiopian Highlands, runs due south, and empties into Lake Turkana on the border with Kenya. The Dawa River is situated in south-eastern Ethiopia, and after rising in the Sidamo highland area it flows south and then east to form part of the border with Kenya and Somalia. In Somalia it joins the Ganale Dorya River to become the Jubba River, which eventually empties into the Indian Ocean. To the north of the Dawa is the Ganale River, which rises and runs more or less parallel to the Dawa, until joining it at the border with Somalia. The Wabi Shabele River (Shebelle River) starts in the eastern Ethiopia Highlands, and flows in a south-easterly direction into Somalia towards the capital Mogadishu. Before reaching Mogadishu, it turns abruptly south-west, runs parallel to the coast, and then either dries up near the mouth of the Jubba River or (during substantial rainfall) reaches the Jubba River and empties into the Indian Ocean. The Awash River starts in the central highlands and is fed by the lakes of the Great Rift Valley. It flows in a north-easterly direction, and eventually supplies a chain of interconnected lakes that ends with Lake Abbhe on the border with Djibouti (Atlas map page 37).

Ethiopia has several major lakes and many smaller ones. Ethiopia's largest lake is Lake Tana, which is situated in the Amhara Region and has the region's capital (Bahir Dar) positioned on its southern shore. Lake Tana is fed by several permanent and many seasonal rivers. Most of Ethiopia's large lakes are concentrated in the Great Rift Valley; the major ones, from north to south, are Koka, Ziway, Langano, Abiyala, Shala (Shalla), Awasa (Hawassa), Abaya and Chamo. There are also some sizeable lakes in north-western Ethiopia, east of the city of Semera (Afar Region), including Lake Abbhe, Lake Gereri, Lake Afambo and Lake Adobed.

Geology and soils

The geology of Ethiopia is complex and varied. The oldest rocks (over 600 million years old) are Precambrian and comprise a wide range of sedimentary, volcanic and intrusive rocks, and these have been metamorphosed to varying degrees over time. Faulting and uplifting caused by tectonic movement is present across the landscape, and this has been accompanied by widespread volcanic activity, giving rise to huge volcanic deposits (magma/lavas and ash) and (igneous) intrusions. The youngest rock types are sedimentary (mostly Mesozoic and Cenozoic), including conglomerates, sands, clays and reef limestone. The sedimentary rocks are mainly a feature of eastern Ethiopia. Volcanic activity continues to the present day, with recent lava flows visible in the northern part of the Great Rift Valley (e.g. between Addis Ababa and Awash). Erta Ale, a

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large shield volcano, is situated in north-eastern Ethiopia, in the northern part of the Danakil Depression, and is noted for its large, active lava lake. Most of the Ethiopian Highlands, the location of the major coffee-growing areas, are dominated by volcanic rocks (lavas and ashes) from the late Cenozoic. These rocks generally produce mineral rich, dark soils, of high agricultural value, which are well-suited to numerous crops, including coffee. Common soil types of the highlands include black soils and red lateritic soils. There are, however, a large number of other soil types in Ethiopia, with coffee farming occurring on many of these.

Natural vegetation, plants and other wildlife

Like many aspects of Ethiopia, the vegetation of Ethiopia is one of contrasts, from the hot, dry and sometimes desert-like lowlands, to the lush, cool forests of the Ethiopian Highlands. There are just over 6,000 plant species found in Ethiopia, of which around 10% are endemic, and 5,200 are flowering plants (angiosperms)[13]. In the *Atlas of the Potential Vegetation of Ethiopia*[5] the natural vegetation types of Ethiopia are mapped and described in detail. The following overview of Ethiopia's plant life is based on this work, and with the permission of the authors we have reproduced their vegetation map and classification for Ethiopia (Figure 5, page 28). Most of eastern Ethiopia is predominately low-lying, and, at least where natural vegetation still exists, is composed of desert and semi-desert scrubland (Desert and semi-desert scrubland (DSS)) and dry woodland and scrubland (*Acacia–Commiphora* woodland and bushland proper (ACB)). The western half of the country is dominated by the Ethiopian Highlands, the location of the country's main crop-lands. Where natural vegetation exists, the main vegetation types of the highlands are: dry evergreen forest, of shrubs and small and large trees, with grassland interspersed (classified as Dry evergreen Afromontane forest and grassland complex (DAF)); and cool, moist tropical forest (Moist evergreen Afromontane forest, and Transition rain forest (MAF and TRF)). These vegetation types typically occur between 1,000 m and 2,500 m. In the lower lying areas (400–1,800 m) between the higher elevation forest types, and in much of the western part of Ethiopia, a dense woodland-wooded grassland exists, characterised by small to medium-sized deciduous trees, interspersed with grassland (*Combretum–Terminalia* woodland and wooded grassland (CTW)). The Great Rift Valley area has its own vegetation type, characterised by mixed acacia woodland and grassland (*Acacia* wooded grassland of the Rift Valley (ACB/RV)); and in the lowlands of the Gambella Region, there is a specific type of wooded grassland (Wooded grassland of the Western Gambella region (WGG)). The mountainous areas of Ethiopia are home to two major vegetation types: the Ericaceous belt (EB) and the Afroalpine belt (AA). The Ericaceous belt (usually 3,000–3,200 m), is composed of shrubby or wooded heath-lands, and is dominated by the heath species *Erica arborea*. The Afroalpine belt (above 3,200 m) is mostly



High elevation wooded heathland of the Ericaceous belt, Simien Mts (northern Ethiopia)

Image: Jenny Wlliams

LEFT
Gelada baboon, Simien Mts (northern Ethiopia)
Image: Jenny Wlliams

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characterised by a sparse, open vegetation type with giant rosette plants, tussock grasses (and sedges), stemless rosette plants, cushion plants, and dwarf shrubs with small, tough (hard) leaves. There are other minor vegetation types, including those associated with freshwater lakes, marshes and swamps, salt lakes and salt pans (Figure 5, page 28).

Ethiopia has a large diversity of native (indigenous) animals. There are also many endemic species, i.e. species found only in Ethiopia, the most notable being the Walia ibex, the Ethiopian wolf, the grass-eating gelada baboon, and the mountain nyala. There are around 270 species of mammal, the most commonly seen include baboon, colobus monkey, grivet monkey (African green monkey) and warthogs. Other large mammals include hyena, hippopotamus, lion, African elephant, kudu, dik-dik, and Grévy's zebra. There are also numerous birds, with 863 species (including 19 endemics) recorded by Bird Life International, and more than 22,000 species of butterflies and moths.

People and culture

Ethiopia is a country rich in culture and history. Important historical and religious sites include the ancient city Aksum (from c. 400 BCE) with its impressive obelisks (stelae), tombs, castles, and churches; the monolithic rock-cut Christian churches of Lalibela (twelfth to thirteenth century); the cliff-face, rock-hewn churches of Tigray; and the imposing sixteenth and seventeenth century fortifications of Gondar. Aksum (Axum) is the locality of the Church of Our Lady Mary of Zion, which is believed to house the Ark of the Covenant, containing the Tablets of Law upon which are inscribed the Ten Commandments. Aksum also has a long-established history with Islam, as does the town of Negash, which is said to be the earliest Muslim settlement in Africa.

Today, Ethiopia has a population of around 100 million people, which is predominately rural and concentrated in the agriculturally superior highlands. In recent decades, urbanisation has increased steadily and is approaching 20 per cent of the population, in-step with cultural change and industrialisation. The country is ethnically diverse, with almost 90 different languages, the most widely spoken being Oromiffa (spoken by the Oromo), Amharic (by the Amhara), Somali (by the Somalis) and Tigrinya (by the Tigrayans). Amharic is the official language of central government and law, although Oromiffa is likely to become the second official language. English is the most widely used foreign language, although it is not widely spoken across Ethiopia. Arabic is spoken in some areas. Christianity and Islam are the two major religions, with a small percentage of traditional religions and faiths. There is a small but long-established Jewish community. Ethiopia is the spiritual homeland of Rastafarianism, or the Rastafari movement, which is centred on the town of Shashemene, although the history of the religion in Ethiopia is very recent (late 1940s). Agriculture, including pastoralism (keeping livestock), is the main source of employment and income generation for Ethiopia's population, employing around 80% of the population[14]. Services, manufacturing, and construction are among the main components of the industrial sector.



Food market in the ancient city of Aksum (northern Ethiopia)

Image: Jenny Wlliams

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Cultivated slopes with remnant *Combretum–Terminalia* woodland species (near Key Afer, southern Ethiopia) Image: Jenny Wlliams

Agriculture

Agriculture is the main driver of Ethiopia's economy, accounting for almost half of gross domestic product (GDP) and a large percentage of export earnings. Most of Ethiopia's agriculture, whether for subsistence or export, is undertaken by small-holder farmers. Principal crops include coffee, the narcotic khat, enset, pulses (peas, beans, lentils), oilseeds (e.g. sesame, niger, lupin, rape), cereals (teff, maize (corn), sorghum, wheat, barely, millet), potatoes, sugarcane, vegetables (including yams, sweet potatoes) and cotton. Coffee, followed by sesame and pulses, are the largest cash/export crops. The most commonly grown cereal (grain) is teff (*Eragrostis tef*), which is used to make injera, the traditional and widely consumed, fermented flat-bread of Ethiopia. Teff, wheat and barley are cool-climate crops, and generally grown above elevations of 1,500–2,000 m. Maize (corn) will withstand warmer temperatures but requires plentiful rain, and so is mostly limited to elevations similar to those that are suitable for the grains above. Sorghum and millet are more drought tolerant and can be grown in lower-lying areas. The narcotic crop khat (*Catha edulis*) is grown in many of the coffee-growing areas but is more drought and heat tolerant than coffee. The pulses and oilseeds are grown in various areas, but especially in the north, and are cultivated in a variety of areas depending on the specific crop species.

Enset (*Ensete ventricosum*), also called the false banana, is an important crop in the southern highlands, feeding an estimated 20 million Ethiopians. Despite looking like a banana its fruits are largely inedible, but the lower part of the stem contains large quantities of starch, which are made into a number of food products. Enset is also used as a source of fibres (e.g. for basket-ware), fodder, and as wrapping material for khat. Common vegetables include onions, peppers, potatoes, squash, and cabbage. Fruits include various citrus and strawberries, particularly from cooler areas, and bananas, avocados, and mangoes from the more tropical (hotter and wetter) parts of the country. In the more humid forest areas, honey, spices, timber and fuel wood are key products for household use and income.

Pastoralism and livestock production is a key part of the agricultural sector, with livestock including cows (of the Zebu type), which are the most dominant livestock animal, followed by sheep and goats. Equine animals (horses, mules, and donkeys) are also an important part of animal husbandry, being mainly used for transportation purposes. In the Rift Valley and adjacent areas and in eastern Ethiopia, camels also play a key role in transportation, while also providing milk and meat. Keeping poultry is very common in rural households, for consumption by the owners and for the local market.

Regions, zones, woredas and kebeles

Addis Ababa, located in a central position in the western Ethiopian highlands, is the capital city of Ethiopia. At an elevation of 2,200–2,500 m, Addis Ababa is the highest capital city in Africa. Ethiopia is divided into a hierarchy of administrative divisions, including regions, chartered cities, zones, woredas and kebeles. There are nine regions (capital towns are given in parentheses): Afar (Semera), Amhara (Bahir Dar), Benishangul Gumuz (Asosa), Gambella (Gambela), Harari (Harar), Oromia (Addis Ababa/Finfinne), Somali (Jijiga/Jigjiga), Southern Nations, Nationalities, and Peoples' Region [SNNPR] (Hawassa) and Tigray (Mekele). Addis Ababa and Dire Dawa are the two chartered cities. The regions are subdivided into zones (second-level division) as shown in Figure 8, page 61; Atlas map page 1 and listed in the Gazetteer (Atlas map page 43). Woredas (third-level subdivision) are generally subdivisions of zones, and each has its own elected council. Kebeles (fourth-level subdivision) are the smallest administrative unit and represent an administrative delimitation at the local level.

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4. Coffee use and consumption

Coffee as a food and other uses

Arabica coffee has been used in Ethiopia as a food and beverage for many hundreds, if not thousands, of years. Its earliest use was no doubt restricted to gathering and eating fruits from trees growing wild in the forests, with semi-domestication and development as a food source probably coming soon afterwards. Coffee fruits are perfectly edible, and can be eaten raw, straight from the tree. When consumed in this way, the fleshy pulp (known botanically as the mesocarp) is eaten and the seed (the coffee bean) is rejected, or 'spat out', as when eating a cherry or similar fruit. However, some people chew and eat the raw bean, and used in this way it is sometimes referred to as 'chewing coffee'. The practice of drying coffee fruits for later use as chewing coffee is quite popular in Uganda (but using robusta coffee). Coffee pulp is very sweet and has a delightful flavour when ripe, qualities which make it suitable for its use as a food and beverage. The pulp is used fresh or, more commonly and conveniently, it is the dried husks (dried pulp) that are used. In the Arabian Peninsula (e.g. Yemen) and in Ethiopia, a beverage made from the husks is known as *qishr* (or *quishir*, *geshir*, *keshir*, *kisher*) but it may also be called *hocha* (or *hoja*) in Ethiopia. *Qishr* is quite popular in Hararge (Harar), where the husks are boiled in water for several minutes before the drink is served hot or slightly cooled. Hot or cold milk is sometimes added. Historians have suggested that *qishir* may have been the forerunner of coffee, particularly as it also known as *qewa* (or *kahwah*), which is thought to be linked to the origin of the name coffee[15–17]. Coffee husks are used to make a similar drink in Central and South America, where it is called *cascara*. More recently, but outside Ethiopia, the pulp has been used in factory processes as a bulk additive to make chocolate bars and other products.

A tea-like drink made from the leaves of Arabica coffee is a popular drink in parts of Ethiopia, and especially in Hararge (Harar), the south-west (e.g. Kaffa and Bench Maji), and the south (Bale). It is also popular on the Boma Plateau in South Sudan. In Oromia it is usually known as *coti* (or *kuti*), although in Hararge the names *qutti* or quxxii are used. The leaves



Coffee leaf tea, coffee husks and dried coffee fruits (from top to bottom); photograph taken in the city of Harar

Image: Jenny WIliams

LEFT

Ethiopian coffee ceremony (Mizan Teferi, south-western Ethiopia)

Image: Jenny WIliams

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are usually picked fresh from the trees, although sometimes fallen leaves are gathered, and either sun-dried or dry-roasted in a shallow pan. When required for consumption the leaves are either broken into small fragments or made into a coarse powder and used in a similar way to tea. Sometimes milk is added. *Coti* is also used as a medicine, for example in the treatment of headaches, fever, and stomach complaints. *Chémo* (or *chamo*) is a variant of *coti*, consumed in parts of Bench Maji and Kaffa. The leaves are roasted and powdered, as in the preparation of *coti*, but other ingredients are added, including ground chilli pepper, ginger, garlic, salt, local basil, and rue. *Chémo* is considered to be invigorating and strengthening, with some users drinking it to keep hunger at bay. It is often taken before a day's hard work and before long journeys, for example.

Traditionally, roasted coffee beans (seeds) are mixed with oils and fats, and with other substances, to make a variety of food items. In the Oromia region, and less commonly in Sidama, coffee is roasted and coated with hot butter and salt, to which spices and sometimes onions and garlic are added. This dish is known as *bunna qélla* (or *buna-quala*), and served slightly warm it is offered as a snack or appetiser, particularly during ceremonies or blessings. Indeed, there is even a specific ceremony based around the preparation and offering of *bunna qélla*. In a similar manner to *bunna qélla*, roasted and ground beans are mixed with butter or oil, shaped into balls and cooled for later consumption. Another variant is to mix the ground roasted beans with butter and sugar to make a paste, to be eaten with unleavened bread[18]. Roasted coffee is also used medicinally in Ethiopia. Tourists may be offered darkly roasted (partially carbonised) ground coffee powder as cure for diarrhoea or a sore throat. Less common is the use of the flowers for inflammation of the eyes, coffee pulp for the healing of wounds, and roasted coffee leaves for stomach ailments.

Roasted coffee as a drink

Despite many legends, and particularly that of Kaldi (Kahlid) the goatherd, and some dubious biblical references, there is no record detailing the date when coffee beans were first roasted and made into a hot beverage. Despite the strong links between Islam and Arabica coffee, there appear to be no records of coffee in the Quran (Koran).

The story of Kaldi the goatherd is the most famous legend concerning the origin of roasted coffee. The story goes that Kaldi was out one day tending his goats when he noticed they had become excited and frolicsome. On closer inspection he noticed they were eating the fresh, red fruits from some nearby trees. Kaldi ate these fruits and found they had a stimulating effect. Later, on the advice of his wife, he took the fruits/beans to a local holy man (or priest) to ask his opinion. The holy man was enraged with Kaldi, believing the fruits to be an evil force, and threw them into the fire. Some minutes afterwards, when they noticed a delightful aroma coming from the burning beans, the beans were removed them from the fire and water added to recapture the essence of the aroma. They found this to their liking, and coffee was born. There are many variants and elaborations of the legend, including those from Yemen. The story is said to originate from the ancient region of Kaffa, which was much larger that the modern-day Kaffa zone.



Ethiopian macchiato

Image: Aaron Davis

The seemingly obvious etymological association of Kaffa and coffee, and the birth of coffee culture and drinking, is widely publicised, although this link appears to be without foundation[15]. The fact that coffee drinking is such an intrinsic part of Ethiopian society and culture certainly alludes to ancient usage. There is some evidence that the use of the coffee pulp to make beverages (see above) predates the use of roasted coffee beans, although the use of roasted (or at least cooked) coffee beans for food could also be linked to the origin of coffee. There are many early associations linking Harar (Hararge, or Hararghe) and the Yemen with the origin of roasting coffee beans to make coffee, with most evidence pointing towards somewhere between the thirteenth and the sixteenth centuries, and with a strong association with Islamic culture. Indeed, the Islamic link is clear: by far the most commonly used name for coffee in Ethiopia is *buna* (from the Arabica word *buun*), and the traditional Ethiopian coffee ceremony has many Islamic references. Detailed accounts of legends, historical usage and the spread of coffee drinking from Ethiopia to Arabia and the Orient, and beyond, can be found in numerous coffee text books[15–17,19].

Modern-day use of coffee

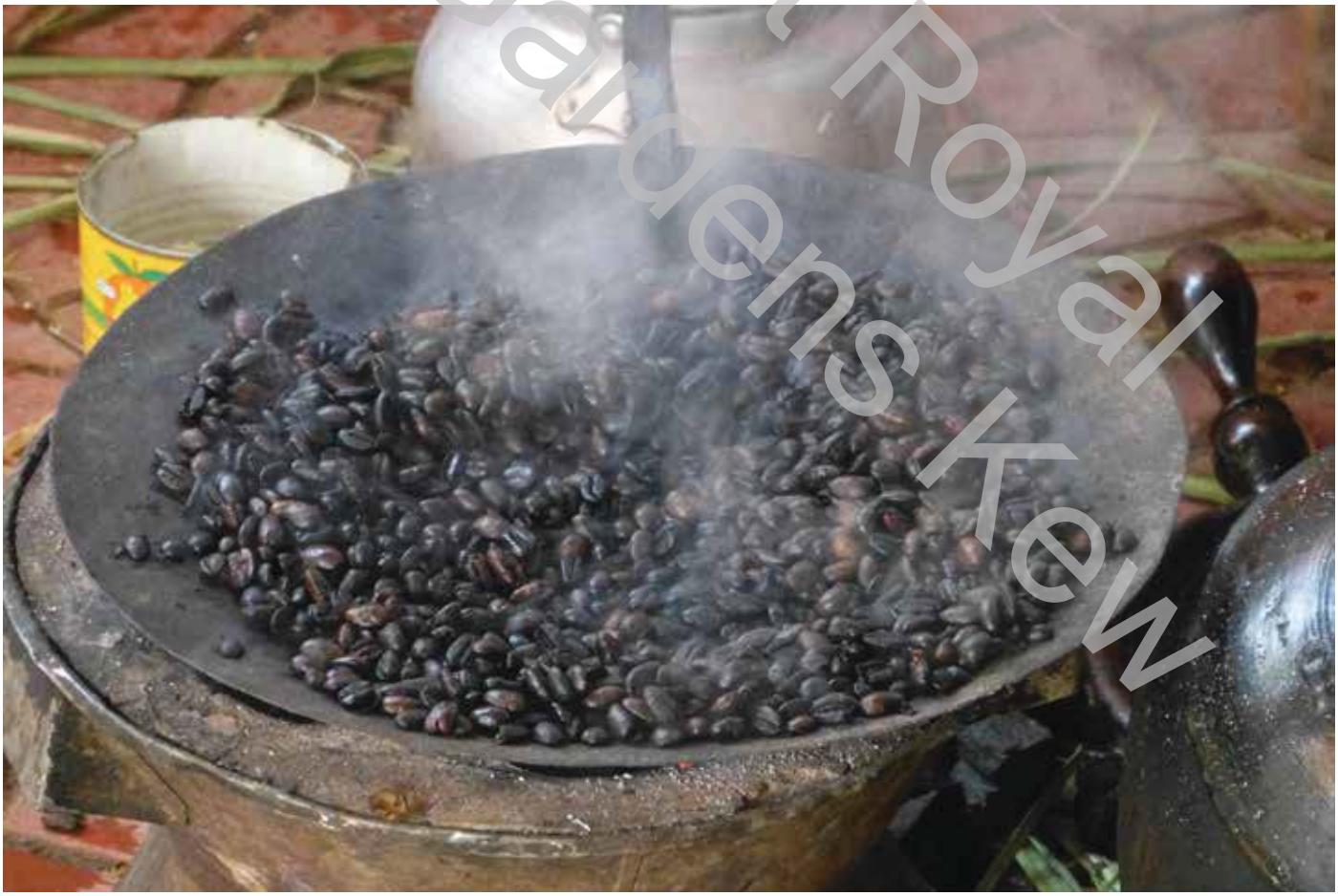
In modern-day Ethiopia coffee drinking is part of every-day life, and for many an important part of community and family living. The Ethiopian coffee ceremony (*tukke* or *bunna*) is well known, and although traditionally performed three times a day, modified and abbreviated version are often seen in hotels and restaurants. In the ceremony, coffee is roasted, made and served using specific traditional equipment, including a

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low wooden table or box-like table (*rekebot*) that holds the traditional ceramic coffee pot, the *jebenna* (*jebena*, *jabena* or *jebana*), small ceramic serving cups (*sinni*), and other items. The roasting part of the ceremony is undertaken using a charcoal burner (*medija*), and a shallow roasting pan (*yebuna mitad* or *metbeshia*), as used in most households and traditional coffee shops. The roasting coffee is turned frequently with a special wooden or metal spatula (*ye buna mequilia*), and after roasting is powdered using a wooden or metal pestle and mortar. The setting and ambiance are also important, including a covering of sedges (*qettema*) on the floor where the coffee is being made and roasted, and the burning of incense. The coffee is re-made and re-served two more times, each serving having its specific order, nomenclature and significance. The ceremony is performed by women and teenage girls. In most towns and villages, women will invite their neighbours for coffee to discuss the news, gossip, and catch-up on the activities of family and friends. A detailed account of the coffee ceremony is given by Tadesse (2017)[15]. Other types of coffee ceremonies are undertaken during births, marriages and other special occasions, with many regional variations.

Outside the home, in every town and village there are usually numerous coffee houses, providing either traditional or 'modern' espresso-style coffee. The traditional type is made in the characteristic fired-clay *jebenna*, and served in small handle-less cups, as in the coffee ceremony. The 'modern' type is made with an Italian espresso machine, to produce a large espresso-like (strong black) coffee, and served in a short glass or small Italian-style espresso cup. Many of the espresso machines have some age, and it can be a delight to see these beautiful old machines being used on a daily basis. A good helping of highly frothed milk can be added to the espresso-like base, to make the Ethiopian version of the Italian macchiato, which is also called a macchiato. Sometimes the froth can be several centimetres high. Ethiopian coffee is almost universally dark to very darkly roasted, and ground to a very fine powder. Coffee-tea (*spreece*, or *chai-buna*) is very popular and is made by layering coffee on top of sweetened (and sometimes spiced) tea into a single glass or cup[18].

In Ethiopia, certain spices and herbs may be added to coffee, including rue (*Ruta graveolens*), cardamom (*Elettaria cardamomum*) and local cardamom (*Aframomum corrorima*), and less commonly ginger (*Zingiber officinale*), cloves (*Syzygium aromaticum*) and cinnamon (*Cinnamomum* species). In certain, places, such as Mizan Teferi, salt is either added or provided in a small spoon. Cow and goat milk may also be added to coffee; or a smaller amount of strong coffee may be added to a much larger volume of rich, warmed milk. Given the longstanding and popular coffee-consuming tradition it is hardly surprising that Ethiopia consumes more coffee per capita than any of the world's other coffee-producing countries. It is estimated that half, or perhaps as much as 60%, of the coffee grown in Ethiopia is consumed within-country.



Roasting coffee over charcoal

Image: Jenny Wlliams

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A coloured engraving of Arabica coffee (*Coffea arabica*) from the book *An Historical Account of Coffee* by John Ellis (1710–1776), published in London, 1774.

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5. Botany of Arabica coffee

Origin and genetic makeup

We will never know the precise details for the biological origin and evolution of wild Arabica coffee (*Coffea arabica*), but based on research on the plant and its close relatives it is possible to make some plausible inferences. From a wide range of scientific research we know that Arabica coffee is formed from the hybrid union of two African coffee species: robusta coffee (*Coffea canephora*) and Nandi coffee (*C. eugenioides*), or perhaps from two other very closely related species (extant or extinct). Robusta coffee has a wide distribution across much of tropical Africa; Nandi coffee is found mostly in the highlands of the central and northern part of the Rift Valley area, and in some localities on the eastern side of the Rift Valley. It is not known where the hybridisation of these two species took place, but it is most likely that it occurred in a locality close to Ethiopia, or perhaps even in Ethiopia itself. Today wild robusta and Nandi coffee are found growing together, or close to each other, in South Sudan, the Democratic Republic of Congo, Kenya, Tanzania and Uganda[20]. However, because the climate has changed over recent geological time, the distribution of these two species is likely to be different today than it was many millennia ago. Indeed, robusta and Nandi coffee could have been present in Ethiopia at some time in the geological past.

The hybridisation of robusta and Nandi coffee was followed by a duplication of the number of chromosomes, a phenomenon known as allopolyploidy. In Arabica coffee the chromosomes doubled, so instead of having 22 chromosomes, as in all other coffee species, there are 44. Arabica is classified as an allotetraploid, because it has four sets of chromosomes. There are consequences associated with allopolyploidy; some good and some bad. Allopolyploidy can potentially make a plant more vigorous and better able to adapt to a wider range of environmental conditions, as does hybridisation alone but without an increase in the number of chromosomes. Another consequence of allopolyploidy, although not universal, is the ability to self-fertilise. In self-fertilising plants, cross pollination (i.e. crossing with another plant) is not required for the fertilisation of the flowers, and thus for the production of viable fruits and seeds. This is a useful attribute for a crop plant, but it has a serious long-term consequence for both wild and cultivated plants. When plants self-fertilise they do not receive genetic material from other (genetically different) individuals, which over time can lead to a severe reduction in genetic diversity (inbreeding). This has probably been the case for wild Arabica coffee in Ethiopia, especially during the early period of its evolutionary life following the initial hybridisation event, when there would have been very limited opportunities for out-crossing. Moreover, available research infers that the hybridisation of robusta and Nandi coffee, and the formation of the allotetraploid Arabica coffee, may have happened only once[21], further limiting genetic exchange.

Despite these limiting factors, wild and cultivated Arabica coffee in Ethiopia possesses considerable diversity, and comprises the world's main storehouse of genetic resources for this crop species. This diversity has specific benefits for the coffee sector, locally, regionally and globally. Most directly, it provides an important source of new planting material for Ethiopian coffee farming, via seed and seedlings, and the intrinsic (genetic) variation that gives rise to the various flavour profiles found across Ethiopia. In the longer-term, protection of these genetic resources should be seen as a key element in the sustainability of the coffee sector in Ethiopia and world-wide.

Distribution of wild Arabica coffee

Arabica coffee was known to the scientific and medical community outside Ethiopia from at least the mid to late sixteenth century onwards. However, it was not until 1753 that it received its formal scientific name of *Coffea arabica*. It was named by the Swedish botanist, physician and zoologist Carl Linnaeus (1707–1778), which is why one sometimes sees the scientific name suffixed with 'L.', the abbreviation for Linnaeus (i.e. *Coffea arabica* L.). The plant was, of course, also well known outside the scientific community before the sixteenth century, especially in Ethiopia and Yemen, and was already being grown and consumed outside Africa and the Arabian Peninsula. Carl Linnaeus, and botanists who came before him, and even those working up until the early and middle part of nineteenth century, believed that the coffee plant came from Yemen (Arabia felix; or in Latin *Arabia felici*), hence the name 'Arabica'. It was not until the mid to late nineteenth that it dawned on the scientific community that this was actually a plant from Africa, and only much more recently that its true biological homelands are the forests of upland Ethiopia and South Sudan[1]. Robusta coffee (*C. canephora*) only became known to the scientific world relatively recently, from around the turn of the twentieth century, although its cultivation and use (as a chewing coffee) in Uganda was recorded in the 1860s, and like Arabica coffee, it has probably been used by local people for millennia.

There are 124 species formally recognised as belonging to the coffee genus (*Coffea*), and they are found throughout Africa, Madagascar and other western Indian Ocean Islands, Asia and Australasia[20,22]. In Ethiopia two species occur naturally (i.e. grow wild): Arabica coffee (*C. arabica*) and *C. neoleroyi*. *Coffea neoleroyi* is a small deciduous shrub or treelet, occurring in seasonally dry forests (in *Combretum-Terminalia* woodland and wooded grassland (CTW))[5] in south-western Ethiopia, at elevations of 600–750 m. It also occurs in eastern South Sudan, and northern Uganda. *Coffea neoleroyi* is a rare species, seldom seen and little-known, even by botanists, and is not used in the production of coffee. Arabica coffee (*C. arabica*)

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grows wild in Ethiopia and South Sudan, although in South Sudan it is restricted to the Boma Plateau, close to the border with Ethiopia. Mount Marsabit in northern Kenya is often given as a location for wild Arabica, although research indicates that the Arabica plants growing on this mountain probably originated from a cultivated source, and that the environment and location is not consistent with natural occurrence[1]. Various literature sources give the Imatong Mountains in southern South Sudan as a location for wild populations of Arabica coffee, but the only known record from these mountains is most likely to be robusta coffee (*C. canephora*), which occurs wild in the Imatongs.

The largest and most diverse populations of wild Arabica occur in the forested upland areas of south-western Ethiopia[23] (Figure 1). The populations are found in the coffee areas of Jimma-Limu, Kaffa, Bench Maji, Tepi, Illubabor, and the western part of Wellega (Figure 1; and Figure 7, page 49). There are also wild populations on the eastern side of the Rift Valley, but these are restricted to forested areas of the Bale coffee area (Figure 7, page 49) and most notably Harrena forest. It has been suggested that the populations in Bale are not indigenous (i.e. they were not originally wild in this area), but were brought there from other localities on the eastern side of the Rift Valley, possibly from Sidamo. Research using molecular (DNA) techniques, however, suggests that Arabica is part of the natural vegetation, and this is supported by the fact that the forests in the Bale Mountains have a plant species composition that is very similar to the humid (coffee) forests of south-west Ethiopia.

In Ethiopia, Wild Arabica is found in nearly all the forested areas with excellent or good coffee (niche) suitability, which are coloured dark green on the Atlas maps. Exceptions include the western part of the Sidamo coffee area, which are mostly covered by dense agroforestry. However, it could be that some or most of the coffee currently being grown in the Sidamo coffee-growing area originally came from wild forests that were once present in the area. Maps showing recorded locations for wild coffee in Ethiopia are found in Davis *et al.* (2012)[1].

Ecology

In Ethiopia and South Sudan, wild Arabica coffee occurs as a small understory tree in moist (humid), evergreen montane forest, at elevations between 950 m and 1,950 m, although 1,200 m is a now a more realistic lower elevation limit, mainly due to the loss of forest at lower elevations. Wild Arabica coffee occurs in Moist evergreen Afromontane forest (MAF), and Transitional rain forest (TRF)[5] (Figure 5, page 28). MAF and TRF forests are composed of a diverse array of evergreen trees and shrubs, and represent what is best described as cool-tropical rainforest. MAF and TRF forest types, sometimes referred to as 'coffee forest', are mostly restricted to the south-eastern and southern part of the Ethiopian Highlands, as shown in Figure 1. Their potential area of cover would have been much greater than it is at present, as much of this forest type has been removed to provide land for agriculture and settlement (see Chapter 7). The potential forest area for MAF and TRF, i.e. where these forest types could grow if it were not for agriculture etc., is shown in Figure 5 (page 28); the actual remaining area for these forest types (collectively termed humid forest) is shown in Figure 1, and in the Atlas pages (Map pages 1–41). Arabica coffee is predominately cultivated in MAF and TRF areas, but in some locations, particularly in the Harar coffee zone (Arsi, West Hararge, and East Hararge), the Amhara Region, and in highland areas in south-eastern Ethiopia above c. 2,000 m, it is cultivated in the wetter areas of the high elevation evergreen forest (Dry evergreen Afromontane forest and grassland complex (DAF); Figure 5, page 28).

Wild Arabica coffee plays a key role in coffee production in Ethiopia, not only as a harvested crop in forest and semi-forest production systems, but also as the source of seeds and seedlings for the planting and re-planting of many of Ethiopia's coffee-production areas. The coffee forests of Ethiopia also have immense value as the main storehouse of wild Arabica coffee genetic resources, which have been used as a source of disease-resistant cultivars and for improving the diversity of the species cup profile (e.g. unusual and superior taste profiles). The genetic diversity of Ethiopia's wild Arabica populations far exceeds that of cultivated variants of Arabica coffee used in crop production elsewhere in the world.

Indigenous populations are often highlighted as a key resource for the medium- to long-term sustainability of global Arabica production.

The humid evergreen forests of Ethiopia are recognised as a globally important hotspot for biodiversity conservation, and are part of the Eastern Afromontane Biodiversity Hotspot[24], one of 34 globally important priority areas for biodiversity conservation. Given that over 50% of the Afromontane region higher than 1,500 m and about 80% of the Afromontane region surpassing 2,000 m is found within Ethiopia, the 'coffee forests' and other traditional coffee production systems in the highlands of Ethiopia are important for biodiversity conservation, both nationally and globally.

Morphology and development

Tree shape and architecture

Arabica coffee is a small evergreen tree (not a shrub), capable of reaching 7 m in height, with a 3 m spread, or thereabouts. At maturity the Arabica tree is more or less triangular in outline, and conical in its three-dimensional shape, due to it having the longest (main) branches at the base of the tree, which progressively shorten towards the top. There is a single upright (orthotropic) main stem (the trunk), the diameter of which varies according to age and growing conditions, from 2–3 cm on young trees to 4–8 cm on older plants, when measured at the base of the tree. On very old wild trees the stem can be 8–13 cm in diameter[25], and in rare cases 15–20 cm[26]. The main branches arising from the trunk may also be termed 'laterals', 'primaries', or 'primary branches'. The main branches are more or less regularly spaced up the main stem, arranged in opposite pairs, and held either at right angles to the main stem (horizontal or plagiotropic) or at low angles (near-horizontal, up to 30°, or sometimes more like 45°). The primary branches give rise to oppositely arranged secondary, tertiary and sometimes quaternary branches, which are often

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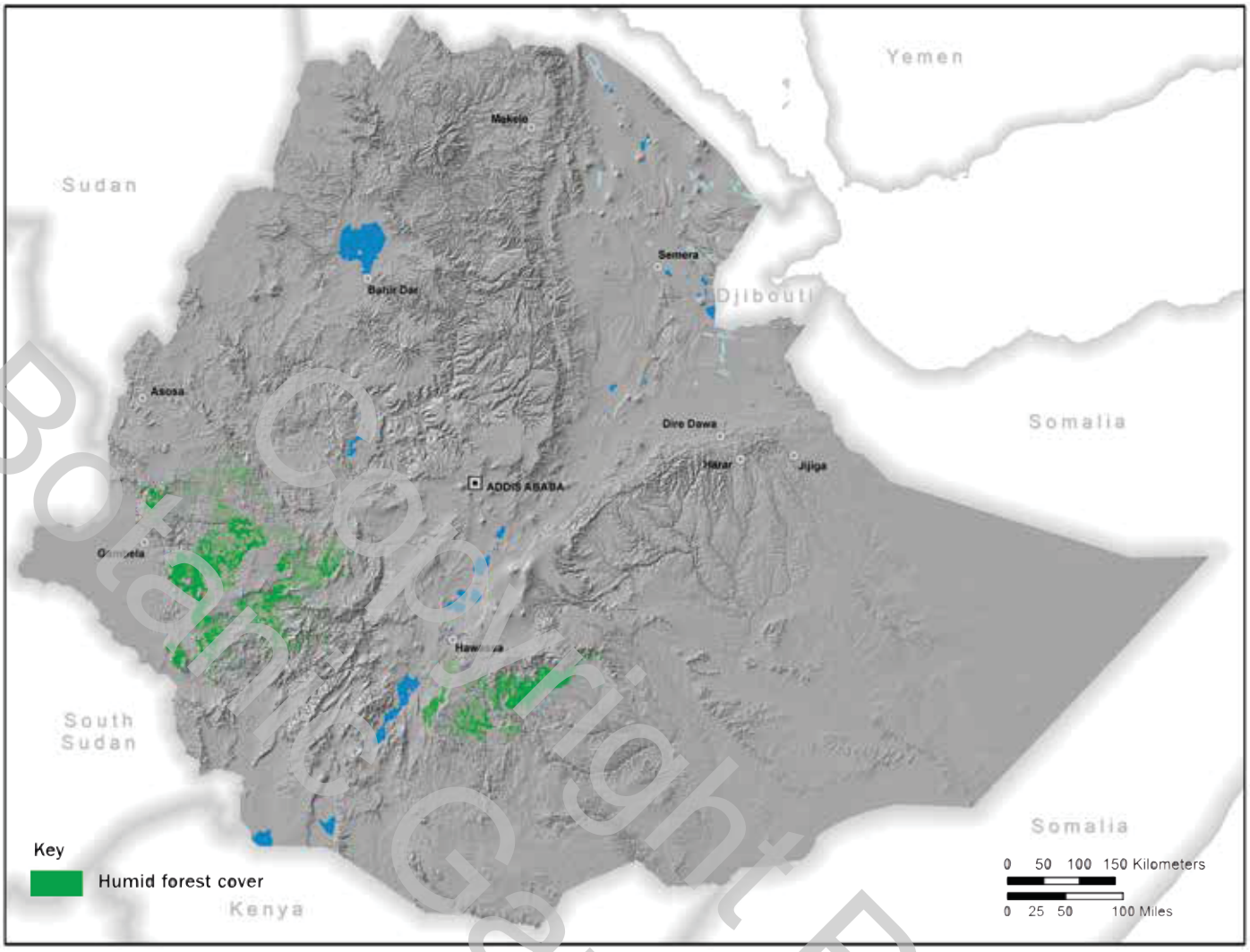


Figure 1. Humid forest cover (2014–15) derived from Landsat 8 imagery. See Chapter 2 for details. Some of the humid forest cover is represented by dense agroforestry (particularly in the western part of the Sidamo area, south of Hawassa).

collectively referred to as 'sub-laterals'. If the tree is pruned, 'topped' (cut off at the top), or 'stumped' (cut down at the base), or if the plant is not growing properly, the shape will be altered. Moreover, with age of 10–20 years or more, the Arabica plant develops into an untidy, leaning tree, with a crooked and/or twisted trunk, losing its regular, more or less conical shape and regular branching pattern.

Arabica coffee trees live for some considerable time, but considering that many other trees live for hundreds of years, and even more than a thousand years, they are ranked as short-lived. There have been no definitive studies of the age of wild or cultivated Arabica coffee trees, but annual tree-ring counts and other evidence suggests that they can live for up to 100 and perhaps even 140 years[15] in exceptional circumstances. In cultivation, farmed Arabica trees start to cease maximum productivity after 10–15 years, and start to reach senescence at about 25 years, but can still live for 40–60 years. The longer-lived cultivated trees are those that have been stumped numerous times. Wild plants usually grow much slower than cultivated plants, reach senescence later, and may therefore reach an older age.

Roots

The following description of roots is largely based on the work of Nutmann[27–29]. The roots of the Arabica coffee plant comprise a tap root, axial roots, lateral roots, (main) permanents, feeder bearers and feeders. The tap root, which is usually branched, extends downwards from the trunk for about 30–45 cm. From the tap root run four to eight axial roots, which grow downwards into the soil for 2–4 m. Also attached to the tap root are the lateral roots, which either run more or less horizontally through the soil to form the main plate of roots, or run downwards and branch in many directions. The permanents are the smaller, woody (cutinised) roots (c. 3 mm in diameter or somewhat wider) arising from the axial and lateral roots, and comprise the main framework of the root system. The feeder bearers, which are also woody, are rather evenly spaced along the permanents, and bear the feeders. The feeders, which are white and non-woody (at least for around three years) and mostly less than 1.5 mm in diameter, are responsible for water and nutrient uptake. The bulk of the feeders are usually 30–40 cm from the soil surface, but this can vary depending on many factors, and particularly on the soil type and water availability:

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in rich deep soils they are deeper; in poorer soils, mulched soils (natural or through farming practices) and irrigated soils, they are mostly closer to the soil surface[17].

Leaves

The leaves are oppositely arranged, i.e. the leaf stalks (petioles) and thus the leaves are held in opposite pairs on the shoots. Situated between the petioles are small bract-like structures called stipules, or more precisely interpetiolar stipules, and these are more or less triangular in shape. The leaves are evergreen but short-lived; each leaf only staying on the plant for about one year, or sometimes longer. All parts of the leaf lack hairs (i.e. they are glabrous). Leaf size is highly variable, depending on age, the environment and genetic origin, but is usually between 7–18 cm long and 3–9 cm wide. The outline shape of each leaf is more or less elliptic (broadest at the middle and tapering towards the ends), and at the tip there is a small but distinct blunt point (the acumen). The margins of the leaves are straight, and neither toothed nor indented in any way; leaves of this type are termed as 'simple'. Each leaf has a midrib (main vein), 6–10 pairs of secondary veins (nerves), and numerous finer tertiary veins. The leaves are rather thin at first but with age become somewhat leathery (subcoriaceous). The upper surface of the leaf is dark green, smooth and shiny, and very slightly waxy; the lower surface is light to medium green, and matt (not shiny). On the lower surface of the leaf, in the axils between the midrib and the secondary veins are small, swollen, pit-like structures called domatia, although these are difficult to see with the naked eye.



LEFT
Young tree of Arabica coffee (Gore, south-west Ethiopia)
Image: Jenny Williams

Prominence has been given to the colour of young leaves as one of the key recognition characteristics for two important early coffee variants (often considered as varieties of *Coffea arabica*), 'typica' and 'Bourbon'. The 'typica' variant has bronze young leaves and leaf tips, whereas in 'Bourbon' these are green. Examination of wild and farmed Arabica coffee in Ethiopia shows that this character is highly variable, and that both types can be found growing in close proximity.

Flowers

The flowers are positioned in the axils of the leaves, i.e. between the (lateral) shoot and the stalk of the leaf (the petiole). There are one to ten flowers in each leaf axil, that is, 2–20 in a cluster (i.e. per leaf pair), which are grouped together in small numbers in structures known as inflorescences. Arabica coffee plants growing in forest or deeply shaded places generally produce fewer flowers, as few as two per cluster. Each lateral shoot produces 5–10, or sometimes up to 12 clusters of flowers depending on the age of the plant, its health and its genetic characteristics. When growing well, each Arabica coffee tree will produce tens of thousands of flowers.

In rain-fed conditions, the dormancy of the flower buds is broken by the first rains of the wet season, but this must be preceded by a dry (resting) period of 3–4 months. Flowering usually occurs 8–12 days after the rains, depending on temperature and other factors. The flowers generally open in the morning and fade by midday or the afternoon, either falling to the ground soon afterwards or staying on the plant for some days in a dry, brown state.

The main part of the flower (the corolla) is white, and is united at the base to form a tube-like structure (the corolla tube), upon which are five (sometimes four or six) lobes (the corolla lobes). Inside the corolla there are five stamens. Each stamen has an anther sac (the structure that houses the pollen), which is held on a fine stalk (the filament); the other end of the filament is attached to the inside of the corolla tube, at the throat (the uppermost part or the corolla tube), between and just below the lobes. The stamens are often referred to as the 'male' parts. In the centre of the flower is the long, slender style, which is terminated by two style lobes, the (stigmatic) surfaces of which receive the pollen. At its base, the style goes through the centre of a structure known as the disc, and connects to the ovary. Each ovary has two compartments (the locules), which each contain an ovule. Once fertilised by the pollen, the ovules develop into the seeds (the coffee beans). The style and ovary are often referred to as the 'female' parts of the flower.

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Flowers of Arabica coffee (Bonga, south-west Ethiopia)

Image: Aaron Davis

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Fruit and seed

The flowers are either pollinated by bees or undergo self-fertilisation, as discussed on page 15. After pollination the fruit starts to develop, initially from a small green, round structure of a few millimetres in diameter, through various stages of ripening to the mature fruit (known botanically as a drupe). The ripe fruit, which is commonly referred to by those working in coffee as the 'cherry', is usually red, rarely yellow, and smooth apart from the remains of the fruit stalk at the base and the disk (formerly the disc of the flower; see above) at the very top. The mature fruit is made up of several layers. On the outside is the fruit skin (the epicarp), inside this thin layer is the watery pulp (the mesocarp), and then the hard, crunchy layer known as the parchment or hull (the endocarp), which surrounds the green coffee bean (the seed). The seed is covered by the silver-skin (the seed testa), a thin layer of cells that turn almost paper-like when dry. Inside, the seed is composed mainly of storage cells (the endosperm), which provide nutrition for the tiny embryonic plant (embedded within the endosperm at the base of the seed) mainly in the form of carbohydrates, lipids and protein.

In total, the coffee fruit takes 8–9 months to ripen. In the first 6–8 weeks after flowering (and fertilisation) the fruits remain small and round and are referred to as 'pin-heads'. Following this, from 8–18 weeks there is a rapid growth phase, when the internal parts of the fruit undertake rapid development and the fruit increases steadily in size. There is then a slow growth phase, which lasts for around 2 weeks[30]. From about week 18 to week 32 fruit development continues, especially the development of the endosperm and the accumulation of dry matter. Finally, from week 26 to week 36 the pulpy part of the fruit (the mesocarp) swells and becomes watery, the fruit skin (the pericarp) turns from green to yellow, and then finally red at maturity. The speed of development depends on numerous environmental factors, including rainfall, temperature, soil, sunshine hours and light intensity. Generally, the fruit ripening stage takes around 10 weeks, during which the sugar content increases markedly.

The seedling and its development

Under natural conditions, animals, including monkeys, birds, and civets (for fallen fruits), disperse the seeds within forests and between forest patches. The sweet and nutritious fruits are ingested by the animals, a process which removes all the pulpy parts of the fruit leaving the seeds intact. The seeds are voided on to the ground within the faeces of the animal, ready for the rains and then germination. Soon after germination the seed is pushed above the soil on the young stem, at which stage it is referred to as a 'soldier'. Inside the above-ground seed are the first two young leaves (the cotyledons), which continue to draw reserves from the endosperm and eventually (after 3–4 weeks) force off what is left of the seed (mostly the remains of the parchment). The cotyledons are vaguely ear-shaped, and therefore look very different from the normal leaves. Shortly afterwards the true leaves appear and further leaf pairs develop. From this stage the young plant will grow and develop to maturity. In cultivation, maturity is defined by the first crop, which takes around 4–5 years from germination. In the wild, growth is usually much slower, mainly due to competition with other plants; the fruiting stage might not be reached until a decade and perhaps even longer, after germination.



Ripe and ripening fruits of Arabica coffee (Harenna Forest, Bale Mts, southern Ethiopia)
Image: Jenny Williams

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6. The coffee climate

Arabica coffee grows successfully, and produces a marketable crop, within a narrow range of environmental conditions. The interplay between rainfall, temperature and seasonality are the main factors governing coffee plant growth, including flowering and fruiting stages. Coffee will become increasingly stressed as the air temperature increases and the soil moisture decreases (due to lack of rainfall), and *vice versa*, within the optimum climatic range for the species (see below). Temperature and rainfall are strongly influenced by seasonality, i.e. the annual weather patterns, as indicated in Figures 2, 3 and 4.

The seasons

The climate of Ethiopia's coffee-growing areas is tropical, but because they occur in highland localities (above 1,000 m) they can be classified as cool-tropical. The seasons are largely defined by rainfall. There are three main seasons: Bega, Belg, and Kiremt (or Kremt).

Bega (October to January/February) — the long dry season. This is when coffee harvesting and processing take place. The severity of the main dry season depends largely on location but also on other physical characteristics, including elevation, slope and aspect. There may be slight to moderate rainfall or barely any at all.

Belg (February to May) — the first rains before the main wet season, which may either represent the early part of the wet season or form a distinct short wet season followed by a short dry period before the main rains. This is the main period for coffee flowering, fruit initiation and early fruit development stages.

Kiremt (Kremt) (June to September) — the main wet season. In areas where the Belg period is distinct from this main wet season, the rainfall pattern is bimodal (east of the Rift Valley); where the bulk of the yearly rainfall is confined to Kiremt, the rainfall pattern is unimodal (west of the Rift Valley). This is the period for the middle and later stages of coffee fruit development. Around the end of September there is a sharp decline in rainfall, as Kiremt comes to an end and the dry season (Bega) begins. During the later part of this season, into the early part of the dry season, is when coffee fruit ripening occurs.

Throughout the coffee landscape, temperatures are generally higher during the dry season and lower in the wet season(s). Seasonal rainfall and temperature profiles for six coffee-growing locations are shown in Figure 2.

Rainfall (precipitation)

Rainfall is the most important factor governing the distribution of coffee farming and wild coffee forests in Ethiopia[10,31,32]. The distribution of rainfall varies greatly across Ethiopia (Figures 2 and 3), according to the season, location, elevation and physical features of the landscape. Clear annual patterns are evident, although rainfall is extremely variable.

The highest rainfall is on the western side of the Rift Valley, in the main South West coffee zone. The coffee areas of the south-west typically receive 1,500–2,100 mm of rain per year. In the southern part of the South West coffee zone there is generally less annual rainfall (1,300–1,700 mm per year). The North coffee zone, including the Amhara and Benishangul Gumuz coffee areas, receives 1,400–1,800 mm per year, although the main rains come later in the year and end earlier, than those in the south-west. This results in a shorter, more intense wet season and a longer dry season (see Bahir Dar, Figure 2).

On the eastern side of the Rift Valley, the Harar coffee zone usually receives lower rainfall than all other coffee areas (800–1,200 mm per year). The Sidamo coffee area in the south is wetter (1,200–1,600 mm per year), and the Bale coffee area somewhere in-between (1,000–1,400 mm per year).

Air temperature

The ideal average minimum temperature for Arabica coffee is 12–14°C, (Figures 2 and 4); temperatures at or slightly above 0°C can be tolerated only for very short periods (e.g. a few minutes to a few hours). The ideal average temperature is 18–22°C, and ideal average maximum (daytime) temperature 25–27°C. Maximum temperatures of 30–32°C are not lethal if they exist for short periods (hours), and if there is sufficient water available in the soil. Extreme temperatures for coffee beyond 32°C up to 34°C, and perhaps even a high as 38°C, can be tolerated for very short periods (a few hours), but only if there is adequate water in the soil. If the soil is not wet enough, then the extreme maximum temperatures for coffee plant survival will be lower; for example, temperatures around 30°C could be lethal within less than 24 hours if the soil is very dry.

Temperature patterns in Ethiopia vary according to the season, location, elevation, and physical features of the landscape. In the coffee areas on the western side of the Rift Valley, the minimum temperature is typically 11–14°C, the average 15–20°C, and the maximum 23–27°C. In the coffee areas on the eastern side of the Rift Valley, the minimum is 9–13°C, the average 16–20°C, and maximum 24–26°C. Elevation has a direct and almost uniform relationship with air temperature, with an approximate decrease of 0.6°C for every 100 m increase in elevation. Nevertheless, other physical factors (e.g. slope and aspect), weather (e.g. rain, wind), and vegetation (e.g. forest cover) will also influence temperatures, depending on location and time of year.

Humidity and other factors

In the coffee areas of Ethiopia, humidity is mainly linked to rainfall and temperature. In the dry season (October to January/February) the monthly average relative humidity (RH%) of a typical coffee-growing area within the South West zone is around 55–80 RH%, and in the wet season (June to September) 90 RH% or higher. There is a considerable difference in humidity between day (low RH%) and night (high RH%). The amount of sun (sunshine hours) is linked to seasonality, with

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greater cloud cover and less sunshine in the wet season(s), and less cloud and more sun in the dry season.

Climate change

It is clear from historical weather station data that the climate of Ethiopia has changed. In particular, there is good evidence that temperatures have increased steadily and significantly throughout Ethiopia, as well as indications that rainfall has decreased in some areas, including some of the main coffee areas[10,32]. Feedback from coffee farmers and coffee-farming communities supports recorded climate data, as does observation of coffee farms and Arabica plants occurring in climate-sensitive areas. Projections for climate change across this century are not encouraging, with temperature increases projected to continue at a steady and significant rate. Changes in rainfall are less certain, with projections ranging from a slight increase to a slight decrease, or little change, throughout this century[10].

These changes will have a substantial negative influence for coffee production in Ethiopia, due to declining climatic suitability in many of the areas that currently grow Arabica coffee (Figure 7, page 49). In terms of a gross simplification, in places where it is too hot and too dry to grow coffee (including the low elevation areas classified as Unsuitable, Marginal and Fair; see Figure 6, page 29 and Atlas map pages) coffee farming suitability is projected to deteriorate (worsen); however many areas that are currently too cold for coffee farming could come into better suitability for Arabica coffee (particularly at higher elevations close to areas that currently have Good and Excellent suitability); and many (but not all) areas that have Excellent suitability should be more climate resilient.

Despite the negative outlook, there could be the potential to substantially increase coffee production in Ethiopia, if new coffee farming areas are created, particularly at higher elevations where it is cooler. Fortunately, Ethiopia is blessed with an abundance of high ground (over 2,000 m), providing substantial potential for so-called 'up-slope' migration to cooler areas as temperatures increase. There could be the potential for a fourfold increase, although a doubling of the suitable land area for growing coffee might be more realistic given all the various constraints[10].

Transitioning in this way would clearly involve some major changes: new coffee production areas would have to be established, during specific time periods and in specific locations[32]. There are indications that this transition is already taking place, with coffee now being grown at elevations previously not seen before (Chapter 10). In short, there could be a route to continued and even expanded coffee farming in Ethiopia, even under climate change, if careful and timely interventions are made. There could also be a positive environmental benefit, as many of the new coffee areas would require significant tree planting in order to provide the right conditions for long-term coffee cultivation.

A non-technical overview of coffee and climate change in Ethiopia is provided in the report *Coffee Farming and Climate Change in Ethiopia: Impacts, Forecasts, Resilience and Opportunities*[32]. The science on which the report is based can be found in the research paper by Moat *et al.* (2017a)[10]. The Atlas, technical paper[10] and summary report[32] can be used together as a base-line resource for scoping local and national climate resilience strategies for the Ethiopian coffee-farming sector.



View from Mt Tulu Dimtu (4,389 m), Bale Mts (southern Ethiopia), with Afroalpine belt vegetation
Image: Jenny Williams

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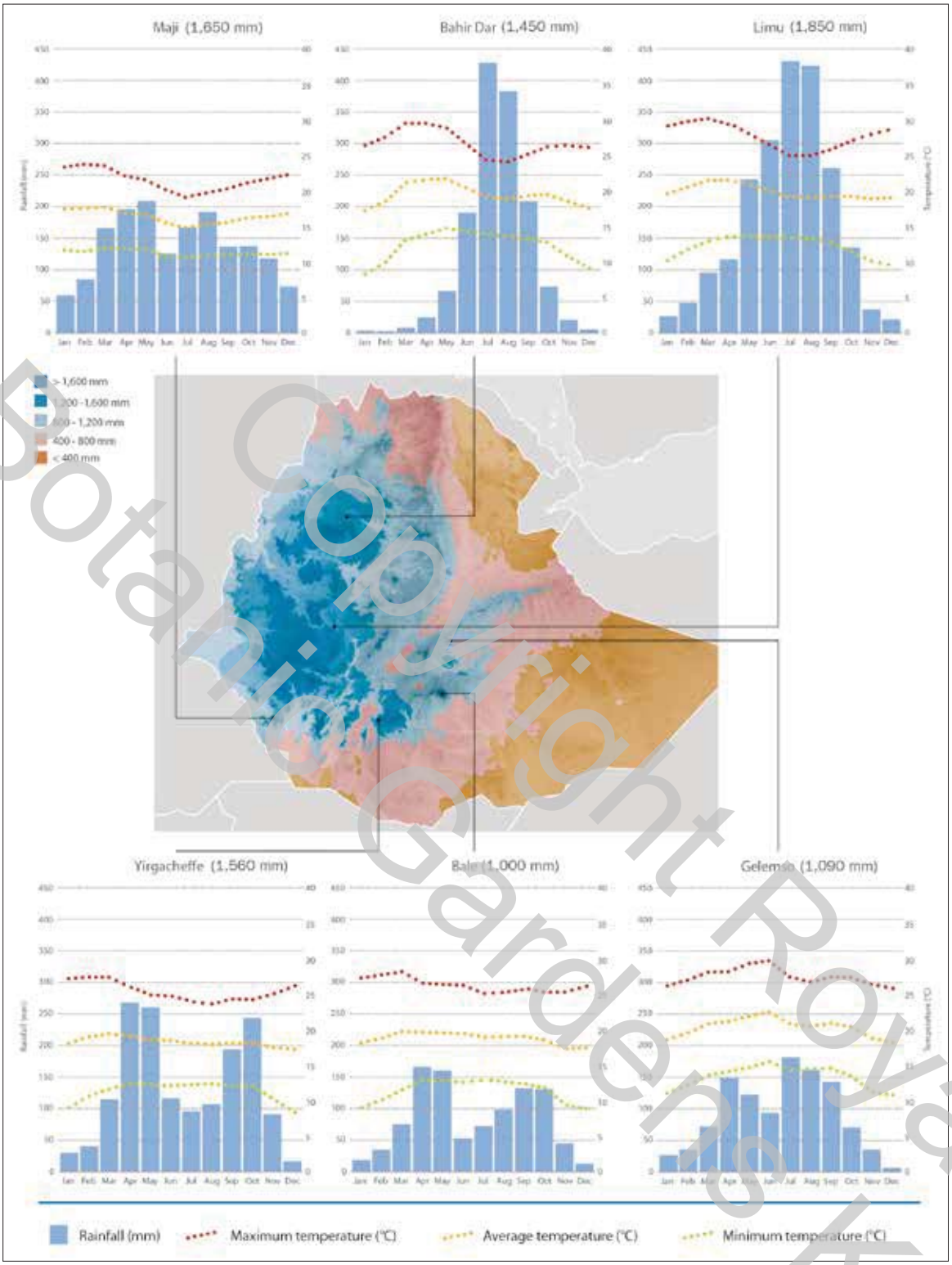
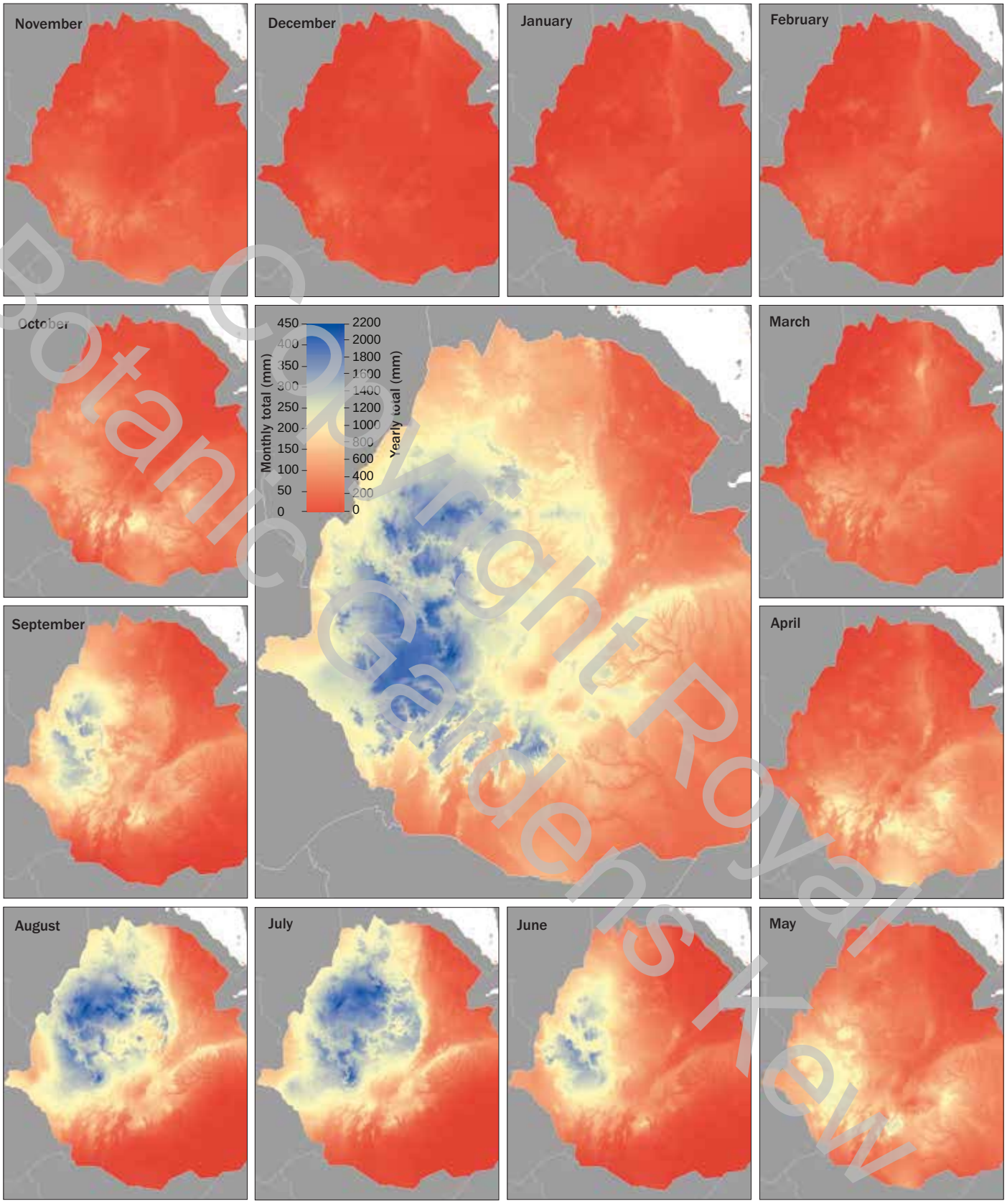


Figure 2. Annual rainfall map of Ethiopia (centre), and rainfall and temperature profiles for six coffee-growing locations. Approximate total annual rainfall for each locality is given in parentheses. Bimodal rainfall pattern (east of Rift Valley); uni-modal rainfall (west of Rift Valley). Graphs based on historical climate data (30-year averages) and WorldClim[11]. Yearly rainfall map of Ethiopia from WorldClim[11].

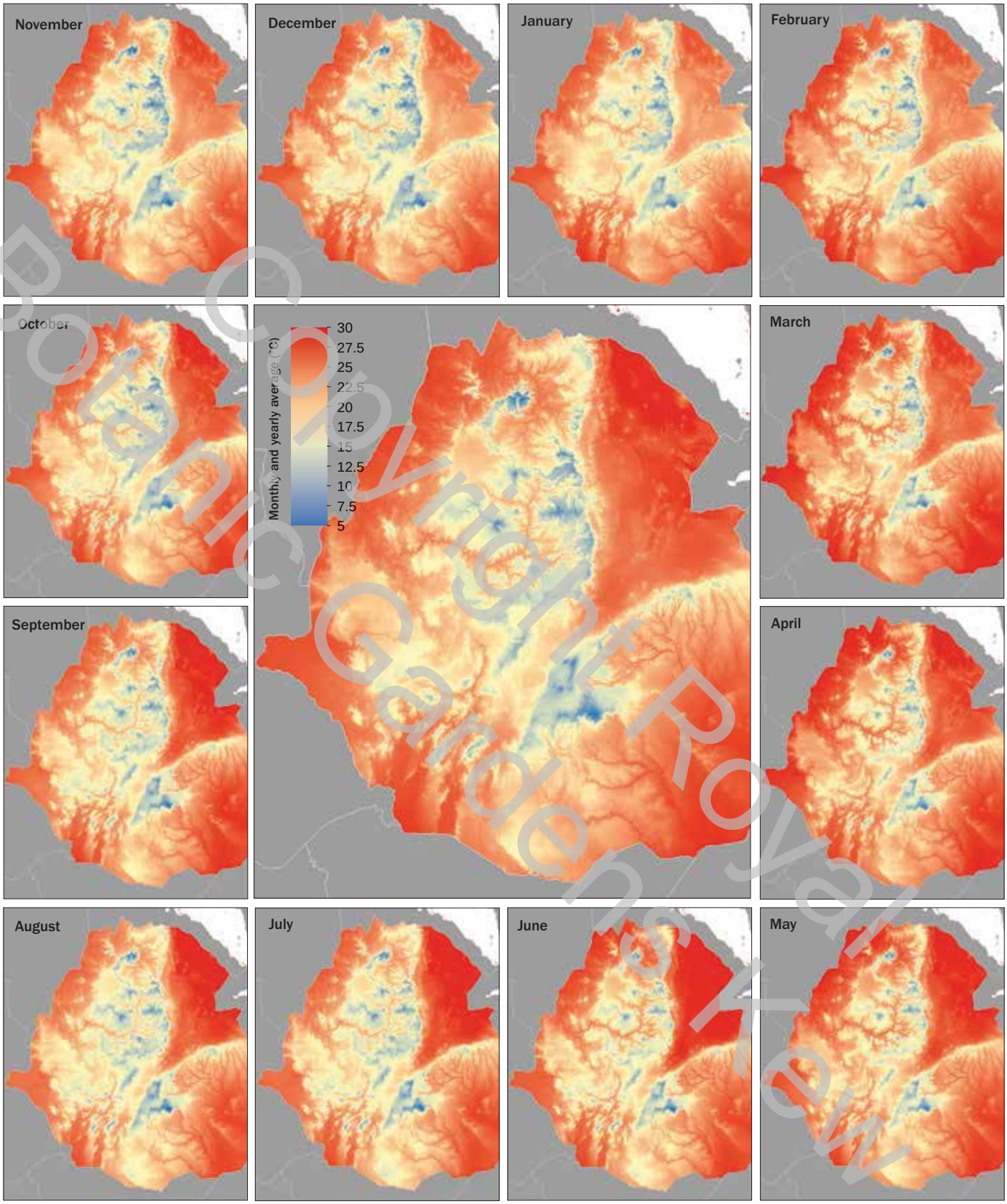
Bahir Dar. (Zege Peninsula). Sufficient annual rainfall, but the dry season (October to February/March) is very dry and coincides with the highest temperatures of the year. The bulk of the rain falls in the main wet season (May/June to September). Coffee suitability is marginal (coffee-growing is possible but often problematic, with poor and very inconsistent yields) and is often negatively influenced by drought during the dry season. **Limu**. Sufficient rain throughout the dry season (October to February) and good rains in the main wet season (May/June to September). Highest temperatures coincide with sufficient rainfall. Coffee suitability is excellent (coffee production good to excellent, with the potential for consistent, high-quality yields). **Maji**. Sufficient rain throughout the dry season (October to February) and good rains in the main wet season (May/June to September). Highest temperatures coincide with sufficient rainfall. Coffee suitability is excellent (coffee production good to excellent, with the potential for consistent, high-quality yields). There is a slight bimodality to main season rainfall pattern. **Gelemso**. Barely sufficient rain throughout the dry season (October to February) and low rainfall in the main wet season(s) (April to September). Highest temperatures may not always coincide with sufficient rainfall. Coffee suitability is rated unsuitable to marginal (coffee-growing is possible but often problematic, with poor and inconsistent yields) especially without intervention (e.g. irrigation). **Bale**. Barely sufficient rain throughout the dry season (October to February), and low rainfall in the main wet season(s) (April to September); low rainfall is offset by slightly lower temperatures. Coffee suitability is good to excellent (coffee production good to excellent, with the potential for consistent, high-quality yields). Yield and quality may be negatively affected in some years (by adverse weather conditions, especially low rainfall). **Yirgacheffe**. Sufficient rain throughout the dry season (November to February) and sufficient rainfall in the main (and slightly extended) wet season(s) (April to October). Highest temperatures usually coincide with sufficient rainfall. Coffee suitability is good to excellent, with the potential for consistent, high-quality yields. Yield and quality may be negatively affected in some years (by adverse weather conditions, especially low rainfall). For further interpretation see Figures 3–8.

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Figure 3. Total monthly rainfall (mm) distribution from January to December (clockwise); see central map (top left hand side) for key to rainfall amounts (mm/month). Total yearly rainfall (mm): central map.



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Figure 4. Monthly temperatures from January to December (clockwise) and yearly (central map) average temperatures.



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Coffee seedling nursery, with semi-forest coffee in background (Yayu, south-west Ethiopia)
Image: Alan Schaller (courtesy of Union Coffee)

7. Agroecology

Coffee farming and natural vegetation

In Ethiopia, coffee is produced within specific agroecological zones over numerous political divisions (see Table 1 and Figure 7, page 49). Most of Ethiopia's coffee is grown in areas that are still covered (Figure 1, page 17), or at one time would have been covered, with humid evergreen forest (Figure 5, page 28). The more precise classification for this type of vegetation is Moist evergreen Afromontane forest (MAF) and Transitional rain forest (TRF)[5]. Currently, about 80% of Ethiopia's coffee comes from these forests or forest-like environments, covering around 20,000 km^2 [10]. The rest is grown in small plots in partial shade or full sun, and covers at least another 4,000 km^2. Humid, evergreen forest is mainly found at 650–2,600 m[5], with coffee-growing mainly confined to elevations of 1,200–2,100 m. These forests are cool-tropical, distinctly seasonal (Chapter 6), and mostly comprise evergreen trees (including wild Arabica coffee) and shrubs, with a high diversity of other plants and associated fauna. In some highland areas, mostly at higher elevations (1,900–2,100 m), coffee farming is undertaken in association with a drier type of vegetation, classified as Dry evergreen Afromontane Forest (DAF)[5], which is dominated by evergreen trees or shrubs, and common native coniferous species (Figure 5, page 28). This type of vegetation is typical of the Harar coffee zone (see page 55), although the natural vegetation has been removed over much of this area.

The association of Arabica coffee and forest is clearly seen at the farm level. Most Ethiopian coffee is grown under the shade of trees (shade or forest coffee), either within forest or forest-like environments, or in farming systems that incorporate specific shade plants — usually indigenous (native) trees or sometimes fruit trees and other crop plants (see below). In some areas coffee is grown with little or no shade (sun coffee), although this probably accounts for less than 20% of total production. Forest (shade) coffee and sun coffee can be considered as two separate production systems but in reality there is a continuum from shade to full sun, and the amount of shade often varies at a single site. Sun coffee farming systems are usually small and mostly fall into the category of coffee gardens, with coffee planted in regular-rows at high density. Sun coffee is usually found at higher elevations (1,700–2,100 m), often near dwellings, and is characteristic of coffee farming in the Harar and Rift coffee zones.

Deforestation

Ethiopia's forest-based coffee farming systems are dependent on the presence of humid forest, particularly for forest coffee (FC) and semi-forest coffee (SFC), as described in Chapter 8. It is clear, then, that deforestation is detrimental for the coffee farming sector. Even though deforestation rates are lower in areas where there is coffee farming[33], it should be recognised that many coffee farming systems are themselves a significant cause of deforestation.

Measuring deforestation over the long term is problematic as there are various classifications of forest types, and large-scale forest change is difficult to measure successfully, even with satellite technology. Nevertheless, it is clear that there has been significant deforestation in Ethiopia, and this includes the humid (Afromontane) forests[34,35] that are associated with coffee production and wild coffee populations. Based on a calculation of potential humid forest cover and what was present in 2014[10], it is possible to estimate that approximately 63% of this forest type has been lost since pre-agricultural times. Deforestation rates vary according to locality, with some areas having much higher deforestation rates than others[32] (Figure 6, page 29). It is believed that around 70% of the deforestation in Afromontane (humid) forests has been caused by small-holder expansion, intensification, and conversion to agroforestry systems[35].

The coffee suitability niche (climate and forest)

In order to grow successfully, coffee must have the correct climate (Chapter 6), microclimate, and soil. In Ethiopia the microclimate is most strongly influenced by the amount of forest cover/shade, or the lack of it, and whether an area is irrigated or not. As there are very few coffee areas in Ethiopia under irrigation, the addition of extra water to the soil is not a major consideration, at least under current cultivation practices. Tree cover has a major influence on ambient air temperatures, and there may be up to 4°C difference between cooler forest/shaded places and hotter unshaded places within the same locality. Tree cover also influences evapotranspiration and humidity, as well as numerous biological (biotic) interactions, particularly relating to soil, soil moisture, aspects of soil chemistry, and biotic features of the soil. The soil must also have the required physical and chemical characteristics, which are largely influenced by the geology and specifically the underlying rocks (Chapter 3). Other factors influencing the microclimate include coffee cultivation practices, the distance between plants (e.g. planting densities), mulching, terracing and pruning (including stumping). Elevation clearly has a huge influence on coffee suitability, but its main affect is directly related to climate (Chapter 6).

Overall, climate and forest/shade (which influences the climate and microclimate) are the main factors influencing suitability for coffee farming in Ethiopia. In terms of the main climate variables, rainfall, temperature, and seasonality are the most important[10]. Rainfall is especially important, given that suitable average monthly/yearly temperatures for Arabica coffee occur across large parts of the Ethiopian Highlands, and the upper and extreme temperature limits for Arabica coffee cultivation are not seen on a frequent or prolonged basis. A broad overview of coffee suitability, forest cover and forest change across the coffee landscape of Ethiopia is given in Figure 6.

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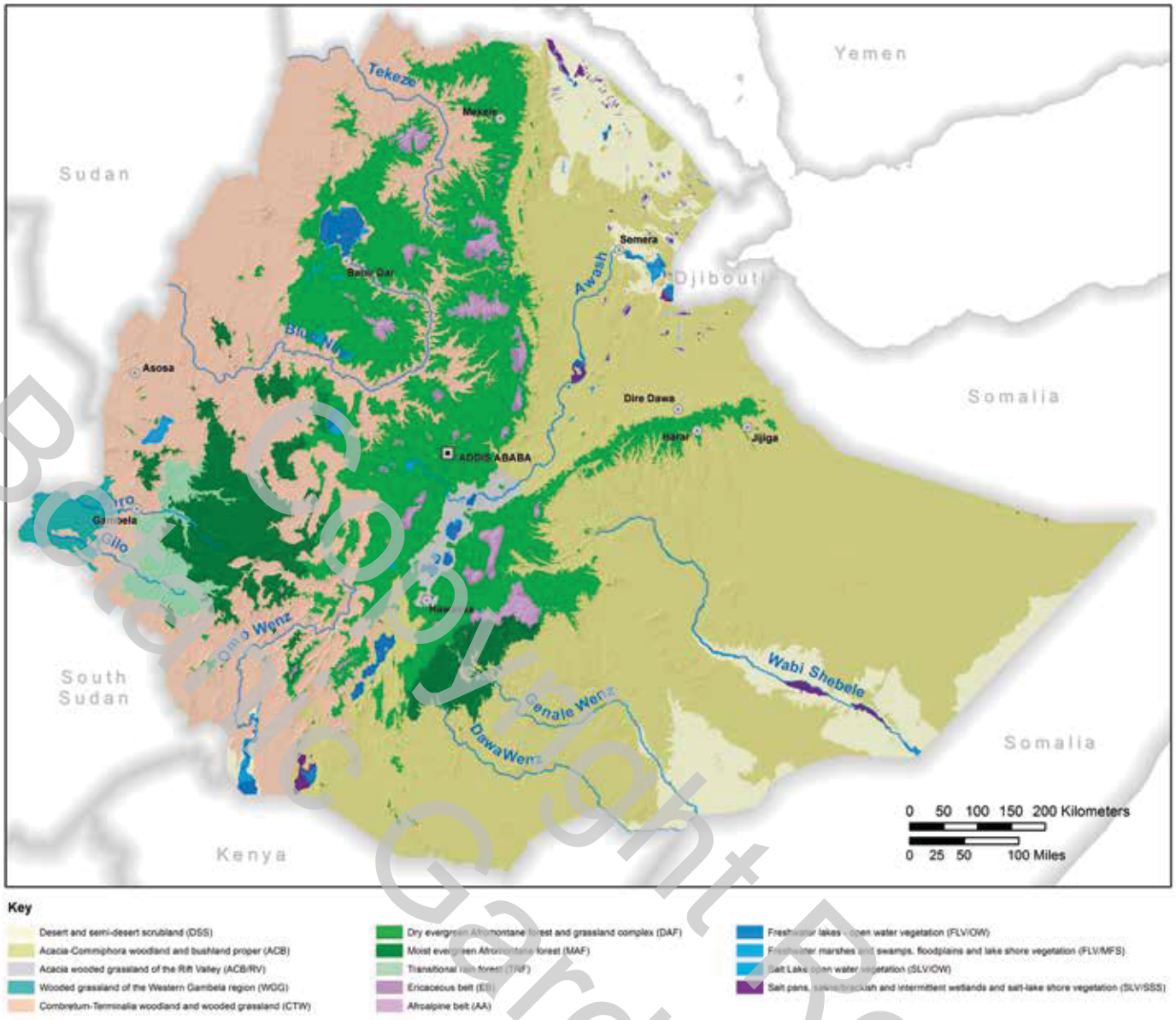


Figure 5. Natural vegetation classification of Ethiopia, from Friis, Demissew & Breugel (2010), *Atlas of the Potential Vegetation of Ethiopia*[5], with major rivers added (see page 5). See key (above) for details of the vegetation classification.

OPPOSITE

Figure 6. Overview of present-day suitability for coffee production in Ethiopia, with modelled coffee suitability (the niche), forest cover and forest change[36]. Map based on climatic variables[10], high-resolution satellite imagery[6], and field observations. See figure legend and text below for further information. Hexagon area is 260 km^2; diameter is 30 km. See Atlas map pages for details.

Forest cover and forest change

Forest change arrows show relative amount of deforestation (c. 2000–2013): polygons without arrows indicate zero deforestation; small arrows ('static'), no or little deforestation; and large arrows ('rapid') a high deforestation rate.

Forest cover hexagons show percentage of forest cover, over a range of 5–70%, from no outline to thick outline.

Coffee suitability (niche)

Potential suitability for coffee-growing or wild coffee forests based on environmental parameters (rainfall, temperature and seasonality)[10].

Unsuitable (no colouration): coffee production is either barely possible or impossible.

Marginal: coffee production is possible but often problematic, with poor and very inconsistent yields.

Fair: coffee-growing is possible and sometimes good, but may require additional inputs (e.g. irrigation, shade or better shade). Yields poor in years with low rainfall.

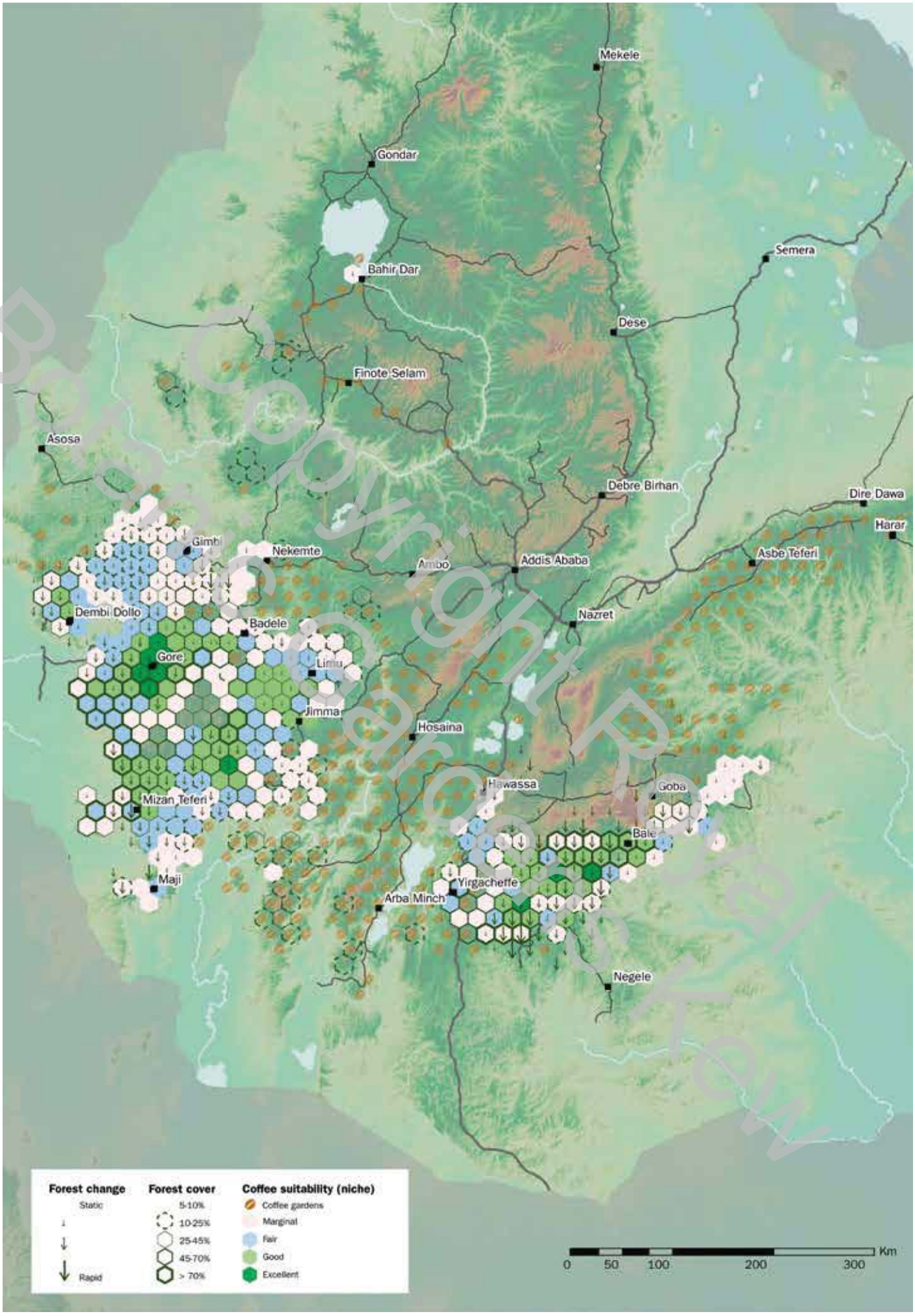
Good: coffee production is good, with the potential for consistent, high-quality yields. Yield and quality may be negatively influenced in some years (by adverse weather conditions, especially low rainfall and high temperatures).

Excellent: coffee production is good to excellent, with the potential for consistent, high-quality yields. Yields and quality can be negatively influenced by adverse weather conditions, but this is less likely than in other areas.

Coffee gardens

The scale of coffee-growing ranges from a few trees to small plots. Yields may be poor and inconsistent, or good, largely depending on inputs (e.g. irrigation) and/or local conditions (e.g. microclimate, or height of water table).

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One-year old Arabica coffee plants in a seedling nursery

Image: Alan Schaller (courtesy of Union Coffee)

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8. Coffee farming

Coffee farming systems

The characterisation of the forest-based coffee production systems into the categories given below was not straightforward, as there are often no clear or definite boundaries between each system. For example, a forest coffee (FC) system with a high level of management will overlap with semi-forest coffee (SFC), and likewise the SFC with forest garden coffee (FGC). Also, some of the larger and more intensively managed examples of SFC and FGC look more like small, shaded plantations, although generally plantation coffee (PC) is greater than 50 hectares (ha), and commonly more than 100 ha, in extent (see below).

In forest-based production systems, there is usually considerable canopy cover, from around 80% (i.e. that found naturally and in some FC examples), or 50–80% canopy cover as per the management of the farmer (for SFC, some FGC, and agroforestry), with a varying diversity of shade tree species present. Ideal shade levels depend on location, and even within a small area the optimum may differ from farm to farm. For successful shade management, there is the need to achieve a balance between the right growing climate and therefore productivity, and the occurrence of diseases and pests. Generally the optimum is 40–60% shade cover, depending on location.

Managed coffee forests harbour about 60–90% of the plant species that would occur in undisturbed natural forests in the same area, depending on the intensity of management practices and the age of the production system[37]. In more intensively managed forest-based coffee production systems (e.g. FGC, agroforestry, and shaded plantation coffee (PC)), where the canopy/shade cover is 30–50%, the diversity of shade trees (and biodiversity in general) is lower[37]. Generally, forests without coffee production have a higher deforestation risk than forests with coffee production[33]; forests with coffee production have lower biodiversity value than natural, undisturbed forest[33]; and biodiversity decreases with increasing intensification, from FC, through SFC to FGC, but with coffee productivity increasing.



Coffee plantation with native (indigenous) tree species (Gesha, Bench Maji coffee area, south-west Ethiopia) Image: Jenny Williams

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Forest Coffee (FC). The FC system uses wild coffee plants, as found in natural forest, with little or no management. This type of production system is not widely practised, especially in undisturbed forest, as productivity is very low (at 50–100 kg/ha, or less). In more disturbed forests, and those with some degree of management, productivity will be higher; in some cases these forests will be in transition to the more intensive semi-forest coffee (SFC) system, as discussed below. FC systems retain the natural forest canopy and all, most, or some of the understory vegetation, and are therefore the best in terms of carbon capture and biodiversity value. Strict FC systems probably account for less than 5% of Ethiopia's total coffee production; all levels of FC production (i.e. strict and slightly managed) are not likely to exceed 10% of total production. Forest coffee is harvested in south-east and southern Ethiopia. Where the land is not owned by the people gathering the forest coffee, it is necessary to acquire a permit from government authorities before harvesting can take place.

Semi-forest Coffee (SFC). The SFC system represents the next stage of intensification from forest coffee (FC), with interventions including the thinning of trees, understory clearance and weeding, and the planting of coffee seedlings. Some of the older SFC areas are derived from the planting or regeneration of native trees species in association with coffee planting, rather than from the modification of natural humid (coffee) forest. In some cases it is difficult to distinguish between SFC and forest garden coffee (FGC). SFC coffee accounts for around 20% of Ethiopia's total coffee production.

Forest Garden Coffee (FGC). This system is the next stage in intensification after semi-forest coffee (SFC), and in most cases the coffee being grown provides a substantial proportion of the farmer's income. FGCs and are typically around 1–2 ha, but sometimes more (e.g. 5 ha or more). The FGC coffee farming area is predominately dedicated to coffee, but there can be other crops growing nearby and sometimes intercropping is used. The canopy (shade) cover in FCGs is less than in FC and SFC, and there is an increase in farming activities, including more regular and denser planting of coffee trees, pruning and removal of shade trees, regular weeding, and pruning (stumping). FGCs are by far the most common of the smaller-scale forest-based coffee farming systems, and the most productive (see section below: Productivity). FGC makes up around 30% (and possibly more) of the total coffee production of Ethiopia.

Coffee Farms (plots). This system of classification is similar to forest garden coffee (FGC), but provides a more general term to include all farms, both forest-based (including agroforestry) and otherwise, including unshaded and lightly shaded systems.

Agroforestry. Agroforestry is similar to the forest garden (FGC) system, and is sometimes included within the FGC system category. However, special mention is required for agroforestry because of the specific characteristics associated with



Coffee garden in full sun (near Hirna, West Hararge coffee area, central-eastern Ethiopia) Image: Aaron Davis

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this production system. Agroforestry systems are generally smaller and more intensive than FGC in terms of the number and diversity of crops being growing. Key crops in addition to Arabica coffee, include enset (*Ensete ventricosum*), maize (*Zea mays*), khat (*Catha edulis*), and yams (*Dioscorea* species). As the name suggests, this is a forest-based system, that mostly uses indigenous trees to provide the shade for coffee and other crops (see section below: Shade plants). Agroforestry farms are typically family run, of between 0.25 and 1 ha, and provide food for the family and income from the sale of farming produce. Coffee is grown for home or local sale, and on larger agroforestry smallholdings for export. In the western Sidamo area, for example, around and near the towns of Aposto, Dilla, Wenago, Yirgacheffe, coffee is almost exclusively produced within an intensively managed agroforestry system.

Garden Coffee (GC) or Coffee Gardens. Garden coffee (GC) is often planted close to dwellings, with the number of trees planted ranging from just a few plants up to around 100. GC is usually part of a mixed cropping system and provide coffee for the household, the local market, and where productivity is good, the crop may be collected from many coffee gardens for export. Coffee gardens are planted in either full sun or in semi-shade, with the shade provided by native or introduced tree species. GC is not part of the forest-based production system, and contributes around 20% of the total coffee production of Ethiopia.

Plantation Coffee (PC) or Coffee Plantations. Coffee plantations are large and intensively managed systems, either privately or state owned. There is no fixed size limit for a plantation but generally they are more than 50 ha (0.5 km^2). Very large commercial plantations (e.g. over 500 ha and up to 10,000 ha) are uncommon. Plantation coffee is the most intensive type of coffee farming in Ethiopia, and comprises uniformly planted coffee trees in neat rows, usually with good access for cultivation activities, farm machinery and harvesting. Depending on the individual plantation, various intensive inputs are made, including organic and inorganic fertilisers, pesticides and herbicides, or some form of non-chemical pest and disease management. On better plantations integrated weed and pest management systems are in place. The coffee trees may be pruned, or stumped, on a regular basis. Soil mulching is practiced on some plantations, including the use of coffee hulling waste. In some plantations, irrigation is used, but so far this tends to be of lower technical sophistication compared to other producing countries (e.g. in South America and Asia). Ethiopian coffee plantations usually incorporate shade (tree) cover, but in many cases the density of shade-tree planting (and therefore the level of shade) is often less than that in forest-based coffee systems, and is much more precisely managed. Other farming activities include the use of soil erosion control in the form of water diversion ditches or bunds (low earth/soil walls), or low-lying hedges of soil/water retaining plants, such as vetiver grass (*Chrysopogon zizanioides*).

The genetic diversity of the planted coffee stock used in plantations is usually less than that in traditional coffee production systems (see above), with selected cultivars and selected lines used. In rare cases on lowland plantations (e.g. around or below 1,000 m), robusta coffee (*Coffea canephora*) may be planted. Harvesting is still done by hand, unlike many large plantations in South America, and especially in Brazil, where harvesting is achieved using specialised farm machinery.

The coffee plantations at Bebeka, in the Bench Maji coffee area (Figure 7, page 49) near the town of Mizan Teferi (Atlas map page 9), is currently the largest in Ethiopia at around 10,000 ha. Previously government-owned, these are now in the private sector. Perhaps the oldest coffee plantation is in Harar (Arsi) near the small town of Gololcha, which dates back to the early twentieth century.

PC is the most productive coffee system in Ethiopia, as illustrated in the section below on productivity. Coffee plantations are not common in Ethiopia at present, although due to higher productivity, and in some cases higher quality,



Semi-forest coffee (SFC), recently planted near Metu, Illubabor coffee area, south-west Ethiopia Image: Aaron Davis

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economies of scale, and good marketing, it is possible that they will increase over the coming decades. At the present time PC contributes 5–10% of total coffee production for Ethiopia.

Shade plants

Forest and shade-based coffee production systems use native tree species. The diversity, i.e. the number of different species used, is largely related to the coffee production system in place. With increased intensification and management (e.g. from FC, through SFC, to FGC), the number of tree species declines. Certain tree species are encouraged, sometimes the more popular types are planted, and in some cases certain trees species are removed if they are considered to be disadvantageous to coffee tree health and productivity. Popular and common indigenous shade species include *Acacia abyssinica* (Leguminosae), various species of *Albizia* (Leguminosae), *Bersama abyssinica* (Melianthaceae), *Celtis africana* (Ulmaceae), *Croton macrostachyus* (Euphorbiaceae), *Cordia africana* (Boraginaceae), *Ekebergia capensis* (Meliaceae), *Erythrina abyssinica* (Leguminosae), various species of *Ficus* (Moraceae), the very popular shade tree *Milletia ferruginea* (Leguminosae), *Olea capensis* subsp. *welwitschii* (Oleaceae) *Polyscias fulva* (Araliaceae) and *Syzygium guineense* (Myrtaceae)[38]. Not only do these trees provide shade for the coffee plants, but they also protect coffee flowers from damage by heavy rain, provide a nectar source for coffee pollinating insects (bees), may fix nitrogen (i.e. the species of Leguminosae), produce mulch (as leaf litter), and assist in soil and water conservation.

In smaller scale, intensively cultivated coffee production systems, such as garden coffee (GC), agroforestry, and some types of forest garden coffee (FGC), non-indigenous fruit trees, such as mango (*Mangifera indica*; Anacardiaceae) and avocado (*Persea americana*; Lauraceae), are used to provide shade. However, both of these trees produce dense shade and take considerable moisture from the soil, so the density of planting in these coffee production systems is low. In areas that grow the staple crop enset (*Ensete ventricosum*; Musaceae), particularly the agroforestry systems in Sidamo (e.g. in Yirgacheffe), this banana-like plant is often very successfully used to provide shade for coffee.

Non-indigenous shade species are mainly used in the initial establishment of shade, and to provide shade and wind protection for young plants, particularly in coffee plantations. These include: the silky oak (*Grevillea robusta*; Proteaceae), a medium sized tree; the castor oil plant (*Ricinus communis*; Euphorbiaceae), a small to medium-sized shrub; and the pigeon pea (*Cajanus cajan*; Leguminosae), a medium-sized, short-lived herbaceous plant.

Productivity

Conversions (to clean coffee)

The standard conversion of ripe, fresh coffee fruits (cherry) to clean coffee (unroasted/green beans) is 5:1 (a multiple of 0.2), which means that 5 kg of fresh cherry would yield 1 kg of clean coffee, after processing and hulling. This conversion rate does not include cherry that is discarded during processing, but rather the loss in weight due to drying and the removal of the pulp and parchment. The conversion of dried cherry (produced by dry (natural) processing) to clean coffee is 2:1 (a multiple of 0.5); thus, a 60 kg sack of dried cherry would convert (after hulling) to 30 kg of clean coffee. For parchment coffee, the conversion is 1.25:1 (a multiple of 0.8), and so a 60 kg sack of parchment would convert to 48 kg of clean coffee. Working from clean coffee, backwards, a 60 kg sack of green coffee approximates to 300 kg of fresh cherry, 120 kg dried cherry, and 75 kg of parchment. When green coffee is roasted it loses approximately 20% of its weight, mostly due to the removal of moisture, so that a 60 kg sack of green coffee would yield around 48 kg of roasted coffee.

The weight unit ‘quintal’ is frequently used and quoted in Ethiopia, for the yield of coffee and other seed crops. A quintal is 100 base units, i.e. one quintal is equal to 100 kg.

Production figures

Ethiopia is Africa’s largest and the world’s fifth largest coffee exporter[39]. In 2016 it exported three million (60 kg) sacks of (green, unroasted) Arabica coffee, equivalent to 180 million kg (180,060 metric tonnes). These figures do not, of course, include the coffee that is consumed in Ethiopia, which is estimated to be about the same amount, or slightly more, than the coffee exported. Since 1990 the amount of Arabica coffee exported by Ethiopia has almost tripled[39]. Despite these impressive figures, productivity per unit area (kg per ha) is low when compared to that in many other Arabica coffee-producing countries, particularly in Central and South America.

The yields quoted below refer to clean (green) coffee. Estimated and calculated values for the different production systems include: forest coffee (FC) 50–200 kg/ha; forest garden coffee (FGC)/coffee plots 300–500 kg/ha, or more productive examples, 600–750 kg/ha; and for well-managed plantation coffee (PC) in areas of high climatic suitability, 600–1,000 kg/ha, or perhaps more. The average coffee yield across the country is often stated to be around 700 kg/ha, although this may be on the high side, and other sources suggest that the average yield is between 300–400 kg/ha. One must also bear in mind the factor of biennial bearing, which often results in marked differences between one harvest and the next (see section: The biennial cycle). The figure of 300–400 kg/ha seems reasonable based on farmer feedback. For example, in Illubabor where a good harvest might reach up to 600–800 kg/ha in an ‘on’ year in the biennial harvest cycle, and 100–250 kg/ha for a poor harvest (in an ‘off’ year). These figures are much lower than the most productive Arabica coffee-producing countries, for example Brazil and Costa Rica, where farms consistently produce around 1,500 kg/ha and 780–1,000 kg/ha, respectively.

The reasons for low productivity in Ethiopia are many and various, including: low planting densities due to the space required for shade trees; climatic constraints (e.g. the long dry season, and general low rainfall); ageing stock (e.g. lack of pruning/stumping, or replacement by seedlings); minimal or lack of fertiliser use (organic or inorganic); diseases and pests; and soil health and soil erosion. Market demand and

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coffee prices influence nearly all of the above factors; farmers generally produce more coffee and of a higher quality when prices are high and stable.

It can be useful to understand the amount of clean coffee produced for each coffee tree. A figure of 5 kg fresh cherry (resulting in 1 kg of clean coffee) per tree is often quoted by farmers and other sources, based on harvesting figures and experience. This is the upper end of the range for Ethiopia, with 3–4 kg of fresh cherry (600–800 g clean coffee) being more realistic, and around 1 kg of cherry (200 g clean coffee) at the lower end of the range. Arabica coffee produces between 1,000 and 3,000 fruits per tree, and so if a single cherry weighs around 1.8 g, that would give a figure of 1.8–5.4 kg of fresh cherry, and 0.36–1 kg of clean coffee, per tree.

The cycles of coffee production

The yearly cycle

The flowering, fruiting and growing cycle of Arabica coffee, is controlled by climate (Chapter 6), which is closely linked to location, and the inherent physiological characteristics of the plant itself (Chapter 5). The dormancy of the flower buds is broken by the first rains of the wet season, which usually start in March or April, depending on the locality. The flowers are short-lived and fragile, and the young fruits start to form soon after fertilisation. In the first 6–8 weeks the fruits remain small and round and are referred to as 'pin-heads'. Over the next 6–7 months the fruits slowly increase in size, and from then onwards, the fruit starts to become fleshy and watery, turning from green, through to yellow or green-yellow, and then finally red at maturity. The speed of development and maturation depends on the season's weather, local climate and elevation (higher elevations being later). Most of the fruit development stages coincide with the early period of the wet season, as does the initiation and growth of new leaves and the growth of the leaf-bearing shoots and the main stem. Fruit ripening coincides with declining rainfall, as the yearly cycle approaches the dry season. In total, fruit development, from fertilisation to full maturity, takes about 9 months. Further details of fruit development are given in Chapter 5. The Ethiopian coffee harvest period usually coincides with the early to middle part of the dry season, between September and November, but it can start as early as August and as a late as February, and sometimes later. There is a lot of regional variation in harvesting time, including: November to early January in most of the South West coffee zone; December to January in (Kelem) Wellega; September to December in the western part of the Sidamo coffee area (South East coffee zone); December to February in Arsi (western part of the Harar coffee zone); January to March in northern locations in the North coffee zone (e.g. on the Zege Peninsula); and October to December (or sometimes as early as August or September) for irrigated farms in the North coffee zone (e.g. at Finote Selam). Whilst



Newly germinated coffee seedlings, or 'soldiers'

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being fairly consistent, regional harvest times are influenced by yearly weather patterns and elevation, with higher elevations being later, and *vice versa*.

After the harvest comes the resting period for coffee, which coincides with the remainder of the dry season. The dry season, which can last for 3–4, or even 5 months, may see light rains or very little rain at all (Chapter 6). During this dry period the flower buds develop, but vegetative (leaf, stem and woody) growth is negligible. There is a considerable amount of leaf-fall in the dry season and the leaves often wilt to varying degrees; both leaf-fall and wilting increasing in hotter, drier conditions. Generally, the coffee plants look tired and unhealthy during, and particularly towards the end of, the dry season. With the onset of the rains the yearly cycle recommences: with flowering, the flushing of the new season's leaves, followed by the growth of the shoots and the main stem, and fruit development.

The biennial cycle

Biennial bearing is a regular feature of Arabica coffee production in Ethiopia and East Africa, and indeed throughout the coffee-growing world. In biennial bearing a good or excellent (bumper) crop is followed by a poor, low-yielding crop in the next year's harvest. For this reason biennial bearing is referred to in terms of 'on' and 'off' years. This phenomenon occurs independently of weather and climate, so that even when climatic conditions are favourable for a good crop, the yield can be poor. There can be a fivefold (× 5) difference between on and off years, although in extreme cases there can be a tenfold (× 10) difference in Ethiopia, as in other areas of East Africa[40]. The biennial cropping rhythm is due to the allocation of the plants resources: in the productive 'on' year, the coffee tree puts its resources into producing the crop at the expense of vegetative growth (stem growth and particularly shoot development and flower bud production); in the 'off' year, the plant must make up for this vegetative shortfall, at the expense of flower and fruit production. Biennial bearing can be reduced or almost eliminated using various means, including pruning, the addition of fertiliser, controlled irrigation and the use of selected vigorous clones or cultivars.

Seed and seedling production

Coffee plants can be propagated by various means, such as cuttings, tissue culture, and grafting, but in Ethiopia the production of new planting stock is almost exclusively undertaken via the sowing of seed. To do this, ripe fruits are removed from the coffee plant and the pulpy parts are removed (i.e. leaving the parchment) either by hand or with a pulping machine, with or without the use of water. Afterwards the seeds are treated in various ways, for example they are often coated with wood ash or powdered charcoal. If correctly prepared and stored, including drying to a level (15–20% moisture) that inhibits pathogens (bacteria and fungi) and yet does not affect the viability of the embryo, the seed may be kept for several months. As seed storage time increases, germination success decreases, and germination time increases, especially after about 3 months of storage, although viability is also strongly influenced by storage temperature and seed moisture. The seeds can also be sown straight away, following preparation. For fresh seed, the germination time is about 7–10 weeks, although in good conditions this could be as short as 4–5 weeks.

The seeds are either sown directly into the ground, into seedbeds with prepared soil, or into polythene pots (polybags), in specially prepared shade beds, mostly fabricated from easily obtainable plant materials such as coppiced tree shoots, grass, and large leaves. The shade beds are either irrigated or the plants are watered with a hose or watering can.

Shortly after germination the seed is pushed above the soil on the young stem, at which stage the seedling is referred to as a 'soldier'. After 3–4 weeks the seed leaves (cotyledons), which are approximately ear-shaped and have wavy margins, force off the old seed. Soon afterwards the true leaves appear and then further leaf pairs develop, at which stage the cotyledons fall off. The seedlings are left to develop in the shade beds for up to one year, by which time they are around 15 cm tall and easily transportable. Seedlings in poly bags tend to have better survival and establishment rates than bare-rooted seedlings, although some farmers prefer the latter because a larger number of seedlings can be transported and planted more easily. Planting is usually undertaken once the wet season is well underway, mostly from May through to August.

Planting densities

Planting distance and spacing vary widely in Ethiopia, depending on personal preference, tradition, local conditions and climate, the soil and other growing conditions. Commonly used planting distances are 1.5–2 m between each plant, and 2.5–3 m between rows. At a distance of 1.5 m between trees and 2.5 m between rows, there would be 2,666 coffee trees per hectare (ha); and with 2 m between trees and 3 m between rows, there would be 1,666 coffee trees per ha. The number of trees per hectare can be many more, especially on farms that are irrigated, with figures quoted of around 5,000 per ha, or even higher. For most Ethiopian farms (i.e. non-irrigated), the number of trees per hectare is usually 1,000–2,000. In areas where the climate is not ideally suited to coffee, the density can be as low as 500 trees per ha. It is often the case that some of the coffee trees are either missing (e.g. they are dead or badly damaged) or are being replaced (by seedlings). Moreover, in Ethiopian shade-based production systems, a considerable proportion of each hectare is taken up by the space required for shade trees.

General cultivation

Pruning and stumping

Pruning in Ethiopia is mainly restricted to stumping, a method of rejuvenating ageing coffee trees by cutting them down, almost to ground level. Ideally this should be undertaken every 8–10 years, but in Ethiopia it is often delayed to around 15 years, or more. Stumping is undertaken during the dry season, after harvesting and before the onset of the wet season, for example from December to February, although the timing varies. The coffee trees are cut down so that only a short length (20–30 cm) or longer (c. 50 cm; known as clean stumping) of main

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stem (trunk) remains; the remaining stem is referred to as the 'stool' in English. The cut through the main stem is made at an angle of around 45°, preferably with a sharp saw, so that water does not collect on the stump and aid infection by pathogens. Sometimes, if a multiple-stemmed tree is being stumped, one of the stems (trunks) is left in place, until the new stems have grown and established (see below). After 3–6 months numerous new shoots develop from the stool, but before they grow too much, the vast majority are cut away (from the base) to leave three to five, well-spaced healthy shoots. One year after stumping, the new shoots may be further reduced in number (e.g. to three) for a multiple-stemmed tree, or reduced to a single main stem, for a single-stemmed tree. If one of the original stems was left from the old tree, it is also removed at this stage. It is not in the farmer's interest to stump all of his trees at once, and so a selected number (or area) are stumped, so that an income can be maintained from the non-stumped trees. Two years after stumping, the coffee trees will come back into productivity and after 3–4 years they should significantly outperform the non-stumped trees, in terms of coffee yield[41]. Research undertaken in Ethiopia shows that other methods of pruning Arabica coffee can increase yields in comparison to the traditional stumping method[42]. Despite the yield benefits of stumping, many Ethiopian farmers are reluctant to stump their trees, probably because of the short-term loss in income, even if the trees are in low productivity due to old age.

Weeding

Weeding is an important part of post-planting aftercare and the general maintenance of coffee farming land. The coffee planting area is cleared of weeds before the planting of new stock, and thereafter two to three times a year, although in drier parts of Ethiopia, only one round of weeding is required. Weeding is undertaken by slashing with a machete, or a similar tool, and the weeds are either left where they are cut, tidied up to the edges of the field, or removed. Herbicides are almost never used, except perhaps in large, intensively managed plantations.

Control of pests and diseases

As in many other coffee-producing countries, diseases and pests can account for a substantial reduction in coffee productivity in Ethiopia. Diseases are generally more problematic than pests. The major diseases of coffee in Ethiopia are coffee berry disease (CBD) and coffee wilt disease (CWD).

CBD is caused by the fungal pathogen *Colletotrichum kahawae*. The CBD pathogen attacks the leaves, flowers and fruits, but it is on the young, developing fruits (1–4 months old) that the symptoms are most readily seen. Initially the fruits have one to several brown and sunken lesions, which develop and then cover the whole fruit, turning it dark brown or black, and wrinkled. The stem on which the affected fruits are attached



Fruiting shoot showing symptoms of coffee berry disease (CBD)

Image: Aaron Davis

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may also become blackened. The fruits may also have scab-like lesions, which develop on the fruit as it ripens. Crop losses per unit area can be as low as 10–20%, or much higher, up to and over 80% in extreme cases. As CBD appears to be linked to high rainfall and high humidity, the management of the farming microclimate is important, and better air circulation (e.g. increasing the planting distances) can help to reduce CBD. Where available and affordable, copper-based fungicides are sometimes used, and these can be effective. The planting of CBD-resistant stock, including that selected from wild Arabica stock, has been effective in some parts of Ethiopia.

Coffee Wilt Disease (CWD) is caused by the fungal vascular wilt pathogen *Gibberella xylarioides*. The symptoms are often first seen on new and developing leaves, particularly in young plants. In the early stages, the leaf tissue close to the midrib and main veins becomes brown and necrotic (dead or dying), and a short while afterwards the whole leaf dries, shrivels and falls from the plant. In mature plants the leaves turn yellowish, wilt and curl, and fall to the ground. In this way even mature plants can become rapidly defoliated, with blackened (necrotic) shoots and fruits (if present). In order to distinguish this pathogen from other diseases, the bark at the base of the main stem should be scraped off: if there is a blue-black staining, particularly at the interface of bark and wood, CWD is the most likely cause[43]. Management of CWD in Ethiopia is undertaken by cutting down infected trees, and sometimes all of the trees surrounding the infected plants, and burning them. Planting CWD-resistant Arabica cultivars can be an effective course of management. Infection rates of planting stock can be reduced by extreme vigilance, sanitary cultivation practices, and the planting of disease-free and disease-resistant plants.

Coffee leaf rust (CLR), *Hemileia vestarix*, is a serious fungal pathogen of Arabica coffee, and the cause of recent devastating crop losses in Central and South America. The most obvious symptom is the presence of pale yellow, mould-like, powdery spots on the under-surface of the leaf. CLR is common on both wild and cultivated Arabica plants throughout Ethiopia, although the level of infection is usually low and with little or no effect on the plant or its productivity. It is not understood why this is the case, but the relatively cool and dry climate of Ethiopia compared to those of many other more tropical Arabica-producing countries (which are hotter and wetter) may be a significant contributing factor. In addition, higher levels of genetic diversity in indigenous Arabica coffee, and the more natural production systems used in Ethiopia, may also contribute to lessening the negative consequences of CLR. There are other minor fungal and bacterial diseases of Arabica coffee in Ethiopia, but generally they do not present any serious problems.



Under-surface of coffee leaves with symptoms of coffee leaf rust (CLR)
Image: Aaron Davis

The main coffee pests in Ethiopia are leaf miner, coffee berry borer (CBB), stem borers, scale insects, and various leaf-cutting organisms. Overall, their influence is minor compared to CBD and CWD. Coffee berry borer (*Hypothenemus hampei*) is a small, brown-black, beetle, 1.2–1.8 mm long; the adults bore into the fruits and the larvae eat the developing coffee beans (the endosperm of the seed), which can lead to large reductions in yield. CBB has only recently been found in Ethiopia, although it could become a major pest[44].

Irrigation

The vast majority of Ethiopian coffee is rain-fed, that is, it relies wholly on the seasonal rainfall. Irrigation is mostly confined to places where water is easily available and can be diverted to the farm using simple, practical means, for example diversion from rivers using trenches. Irrigation is mainly practiced in Amhara and Benishangul Gumuz coffee areas (North coffee zone), and in the north-eastern part of the Oromia Region in the Harar coffee zone (Figure 7, page 49; Table 1, page 50). In the Amhara Region, the town of Finote Selam and places close to this town, are particularly noted for the irrigation of coffee using rivers and streams.

Feeding (use of fertiliser)

The use of fertilisers is generally minimal compared to that in many other coffee-producing countries, with the exception of the larger and better managed plantations. In most cases, feeding is either zero or minimal, and if undertaken is largely restricted to the use of composted animal waste products and composted farm and household waste, in other words, by organic methods. The application of fertilizer, and particularly nitrogen, can significantly increase coffee yields.

Planting stock (landraces, farmer's lines, heirloom varieties and cultivars)

All Ethiopian coffee planting stock was originally derived from the country's wild populations of Arabica coffee. Even today, much of the seedling-derived stock is sourced directly from the forest. A large proportion, however, has been selected and developed by Ethiopian coffee farmers and agriculturalists in order to capture specific traits, such as higher productivity, ease of cultivation, and resistance to certain diseases. These selections are referred to as 'landraces', 'farmer's lines', 'farmer's varieties' or 'heirloom varieties', although the last of these terms is often used as a general term to denote a

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Under the canopy of mature coffee trees (Yayu, Illubabor)

Image: Emily Garthwaite (courtesy of Union Coffee)

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mixture of coffees gathered from several or many farms in a specific locality. There are many hundreds of Arabica coffee landraces in Ethiopia, most of which are specific to their respective place of selection. It is often said that more than one landrace is planted on a single farm, each used for a specific purpose, but this is not the case on smaller farms. Characteristics of tree shape, leaf colour, weight, shape and size of fruits and beans, as well as roasting features, are used to distinguish landraces and may feature in the naming of them. A useful review of landraces is given by Gole *et al*. (2016)[38], including a list of traditional landraces recorded in different coffee-growing localities. The evaluation of Ethiopia's Arabica landraces needs further careful research, particularly at the molecular (DNA) level.

Cultivar is the preferred formal term for cultivated varieties, the term being composed from parts of these two words, i.e. 'culti' and 'var', to give cultivar. The term variety should be reserved for formal, botanical (naturally occurring) varieties. The term variety is, however, widely used in the coffee sector, as is 'varietal', which has probably been adopted from the wine sector. In the older literature, certain origin-specific Arabica variants are often mentioned. For example, 12 'coffee types' are listed by Sylvain (1958)[26]: Ennarea (or Ennaria), from the modern-day Jimma-Limu coffee area; Kaffa; Agaro; Cioiccie; Irgalem, an earlier name for Yirgalem; Dilla; Arba Gougou; Harar; Zeghie (Zege); Loulo; Wolkitte, now called Welkite; and Wollamo (an area situated around the town of Soddo). Nekemti (or Lekemti, and similar name variants) was another commonly used name, for the coffee originating from areas close to (but mostly to the west of) the town of Nekemte in East Wellega. A few of the cultivars listed above make use of the colour of the new leaves and leaf tips (bronze vs. green), which has been given prominence for recognising two major coffee types being grown outside Ethiopia, i.e. 'Bourbon' and 'typica' (see Chapter 5). Although the numerous names listed above appear in coffee research literature, many of them have little practical application today. Nevertheless, provenance still forms the basis of the modern-day classification for Ethiopian Arabica coffee diversity (Chapter 10), and four names (Harar, Limu, Sidama/Yirgacheffe and Wellega) provide the group names for the 37 coffee cultivars distributed by the Jimma Research Center (JRC)[45]. These cultivars were developed to be high-yielding and disease resistant (to CBD)[46], and several million of have been distributed to farmers across Ethiopia.



Harvested coffee fruits (fresh cherry)
Image: Alan Schaller (courtesy of Union Coffee)

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9. Coffee harvesting and processing

Factors influencing quality and taste

The quality of unroasted (green) coffee depends on many factors, including those mostly outside human influence, such as climate, geology/soil, and genetics (except in the case of plant selection); and those directly influenced by the primary producer, such as farming practices, harvesting and post-harvest processing. Climate is a key factor, as temperature and soil water availability (mainly due to rainfall) have a direct bearing on the growth of the plant, flowering, and in particular, the development of the fruit. Elevation has a direct bearing on the local climate, and other factors such as light levels and the quality of light (e.g. ultra violet (UV) light). Soils can influence the crop in various ways, including the way the soil retains and makes water available to the plant (physical features), and by virtue of its chemical (mineral) composition. Arabica coffee variants (e.g. cultivars and landraces; see Chapter 8) have specific quality and flavour characteristics, including body ('fullness' or overall feel (light, medium, or full) of coffee in the mouth), acidity and flavour notes. Many of these characteristics are encoded within the DNA of the plant but are influenced in various ways by the environment. Thus, there is a close interplay between the genetic makeup of the plant and its environment. Importantly, the environment influences the chemistry of the coffee bean (seed) and its external fleshy parts (the pulp), and this has a direct bearing on quality and taste.

Included in the narrative of Chapter 10 (The coffee areas) are overviews and examples of the various flavour profiles for different coffee areas of Ethiopia, which were collated from commercial tasting (cupping) descriptions and dedicated cupping sessions undertaken for the Atlas. It is clear from this information that 'origin' (or *terroir*) is a very real phenomenon in Ethiopia. It is also important to remember that for Arabica coffee in Ethiopia both climate and genetic identity[47,48] are tightly linked to location.

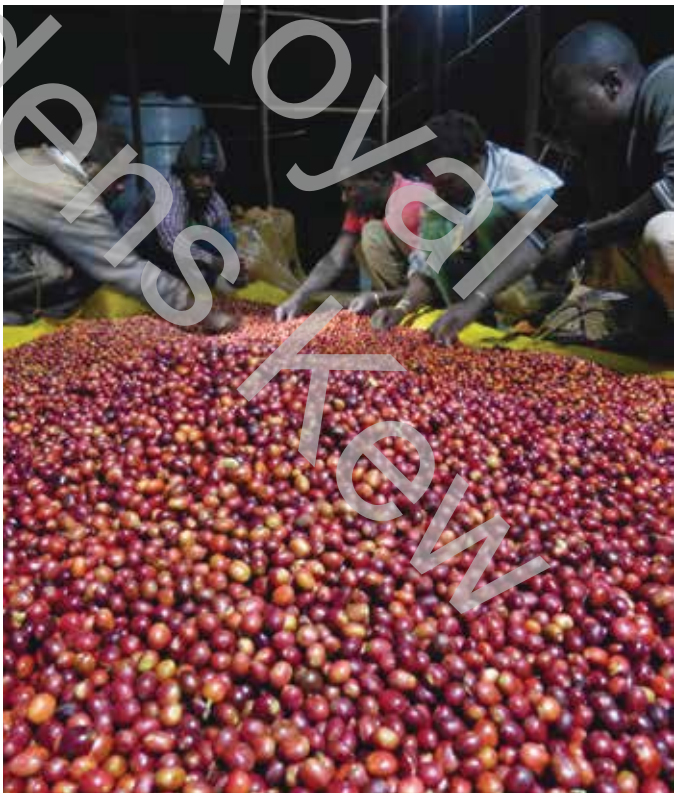
Whilst it may be difficult to pinpoint a flavour profile to any specific coffee area, the differences between (and even identification of) many of the coffee areas can be made by experienced coffee tasters (cuppers). There is an unmistakable distinction in flavour profiles between areas east and west of the Rift Valley (see Table 1 for division of coffee areas): on the eastern side of the Rift Valley (e.g. Sidamo, Bale, Harar) the coffees typically demonstrate bolder flavours, with more pronounced fruit notes, compared to those from the western side of the Rift Valley (e.g. Limu, Kaffa, Wellega). Overall, Ethiopian Arabica coffees stand out from domesticated cultivars grown outside Ethiopia due their more complex flavour profiles.

It should also be made very clear that in addition to the above factors, harvesting and post-harvest processing have substantial influences on the taste and quality of Arabica coffee, as outlined below.

Harvesting

All Ethiopian coffees are harvested by hand-picking, which is a very labour-intensive and skilled process. The colour of the fruits (cherry) at harvesting, which equates to the state of maturation, is critical to cup quality. Varying degrees of red represent the fully mature stage of the fruit, but an even, medium to rich red is mostly sought by well-trained and conscientious pickers. Green, immature fruits, often referred to as 'quakers', are underdeveloped and lack the high sugar content and acidity level found in the mature fruit (and bean), giving coffee a 'dry' mouth-feel (astringency) and a grassy or straw-like taste. In addition, the beans are usually light in colour and weight and do not roast properly. Over-mature fruits are deep, dark red or purple-red, and should be avoided as they can give the coffee a sour (hence the term 'sours') or fermented taste; in the worst cases, the beans produce foul-tasting coffee, and these are commonly referred to as 'stinkers'. If processed correctly, ripe fruit yields sweet, clean coffee, without the defects mentioned above.

Picking is either done cherry-by-cherry, or by stripping a shoot bearing a large proportion of ripe cherry in a single action; the former method improves coffee quality. The coffee fruits do not usually ripen synchronously, with trees bearing green (unripe) and red (ripe) fruits at the same time. Pickers often have to return to the same trees multiple times, and up to five times, to harvest all the mature fruits. This considerably extends the harvesting season for any one farm. Sometimes



Pre-sorting coffee fruits (cherry) prior to pulping and washing

Image: Jenny Williams

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Sun-drying coffee fruits (cherry) on a concrete patio Image: Jenny Williams

there is an early 'fly-crop', which is either picked or not picked; picked fly-crops may form part of the overall harvest, or may be picked early and discarded with a view to improving the main harvest. During harvesting the cherry is placed in a small container or basket and then put together to fill a standard- sized sack for transport to either the drying (for naturals) or washing (for washed coffees) station (see below). The coffee bags containing the cherry are weighed, either at the farm/co-operative or the processing centre, so that the weight can be ascertained and payment made to the picker(s), or to middlemen (*akrabi*) who trade between pickers and other buyers. The interval from picking to processing is critical, and in most cases the fresh cherry must reach the processing area as soon as possible and at least within a day of harvesting, otherwise the cherry will start to ferment and quality will be negatively influenced.

Initial post-harvest processing

After harvesting the fresh cherry is transported to a processing station, where it is weighed and recorded for payment and/or accountability, if this has not already been done. Regardless of the subsequent processing steps, the cherry then receives its first level of sorting. The cherry is spread onto the floor, which is often covered with a tarpaulin, or something smooth and relatively clean, and rapidly sorted by hand to remove the worst green (unripe) and very dark (over-ripe) fruits. Badly bruised and other defective fruits are also removed, along with any twigs (branch shoots), leaves, and other unwanted material (particularly stones, metal objects, insects and other small animals, etc.). Rejected cherry, and particularly under-ripe and over-ripe fruit, is often collected together and used in the households of the coffee workers. Once this first sorting has taken place, the coffee is ready for one of the two major steps in processing: either dry (natural) or wet (washed) processing.

Dry-processed coffees predominate in Ethiopia. Wet processing is common in the Jimma-Limu coffee area and western Sidamo, (including Yirgacheffe) and suitable localities in the Kaffa, Illubabor and Wellega coffee areas (Figure 7, page 49), although isolated washing stations occur throughout Ethiopia; further information is provided in Chapter 10. The use of small-scale, low-cost, wet-processing systems, notably using the Penagos® depulper, allows wet processing in areas that have



Sun-dried coffee fruits (dry cherry) Image: Alan Schaller (courtesy of Union Coffee)

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good suitability for high-quality coffee, but lack the resources to make significant investment in processing. The other major attribute of the Penagos® systems is that they use limited amounts of water, and can thus be placed some distance from rivers or major sources of fresh water.

Dry (natural) processing

Dry (or natural) processing represents the age-old, traditional methods of processing coffee in Ethiopia, and in many places outside Ethiopia. An estimated 75–80% of Ethiopia's coffee is processed in this way, requiring a low level of investment in terms of equipment and labour. Moreover, the requirement for low rainfall and low humidity during the drying of coffee cherry suits the climate of Ethiopia, which has a long, marked dry season that coincides with harvesting and processing. After harvesting and initial sorting, the fresh coffee fruits are spread out in a thin layer (2–6 cm deep; depending on the volume of coffee) outdoors, in the open air, to dry 'naturally' in the sun. The coffee is either dried directly on the (dry, earthen) ground, on woven mats, on tarpaulins or even on the tarmac roadside, or, preferably, on specially constructed concreted areas (patios) or raised drying beds (often called African beds). African beds consist of wooden frames covered with mesh of some description (made of natural materials, plastic, or wire), which holds the coffee off the ground. The raised mesh considerably improves air circulation and thus drying, and keeps the coffee out of the reach of farm animals (chickens, goats and dogs) and sources of foreign matter. Irrespective of the where the coffee is dried, it is turned frequently to enable proper drying and to avoid mould and fermentation. When the cherry is dried on concrete patios, large wooden rakes or pushers are used to turn the coffee. Plastic sheeting may be used to protect the drying fruits from rain, and even night-time humidity and morning dew, especially when raised beds are used. After 2–4 weeks of drying, depending on the weather conditions and other factors, the fruits blacken and the pulp shrinks and hardens, and the drying process is complete. Throughout the drying process the moisture content of the drying cherry is monitored, preferably with a moisture meter. The cherry is dried so that it has a moisture content of between 12–20%. In Ethiopia it is quite common to see patio and ground-dried dried coffee covered with a white or greyish covering of mould. This influences the quality but if kept to a minimal level the mould should not excessively influence the taste of the coffee.

Wet (washed) processing

Wet processing of coffee is a relatively modern method, which probably first started in Ethiopia in the 1950s. Only in the past few decades has it become more widely established, mostly being undertaken in areas of good productivity and and where high-quality coffee is required. In this process, pre-sorted, freshly harvested cherry is first depulped, using depulping machinery (the wet-mill), whereby the fleshy, sticky part of the fruit (the pulp) is mechanically stripped from the coffee bean in combination with a flow of water. Once stripped of the pulp, the parchment coffee (i.e. with the parchment (endocarp) still present) remains covered with



Pulped coffee in the depulper Image: Jenny Williams

a thin layer of the pulp (often referred to as mucilage), and this has to be removed by fermentation. For fermentation, the parchment coffee is diverted from the de-pulper into concrete fermentation tanks into which water (usually river water) is added. Fermentation usually takes 12–36 hours, the exact time depending largely on the temperatures of the air and water, but also on the type of coffee being produced (see below). Fermentation breaks down the remaining sugar-rich mucilage attached to the parchment through bacterial (microbial) action, leaving the parchment free of pulp. After fermentation the beans are given two to four short washes using clean water, which removes the decomposed mucilage and any foreign matter. The parchment coffee is then placed onto small purpose-built drying racks for further hand-sorting, and afterwards spread onto raised drying beds (African beds; see above) for drying. Like dry-processed coffee, the drying coffee needs to be frequently turned and monitored to make sure that it is dried to the correct moisture level, and that the drying is neither too slow nor too fast. Generally, the parchment is dried more rapidly in the earlier stages of drying, but not so fast that the parchment cracks. Drying times vary depending on weather conditions and drying bed management, but the usual drying period is 10–15 days. On some farms, moisture meters are used to monitor the moisture content, which for the dried parchment should be 10–12%. The dried parchment varies from a pale straw to pale yellowish colour.

Dry vs. wet processing

Generally, wet-processed coffees are considered to be of a superior and more consistent quality compared to dry-processed coffees, although this matter is regularly debated by roasters, baristas and coffee-drinkers. Washed coffees are generally considered to be 'cleaner' and more delicate in the cup (i.e. during drinking), lighter-bodied, and with a brighter, better-defined acidity and brighter fruit notes. Washed coffees are also often said to be more balanced (i.e. lacking particularly strong tasting notes or biases). Dry-processed

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Coffee washing station

Image: Emily Garthwaite (courtesy of Union Coffee)

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(natural) coffees tend to be fuller bodied, fruitier, sweeter and less acidic, although in some cases the acidity is more pronounced and easier to define. Choosing between the two types often comes down to personal preference. Some drinkers prefer the more characterful and interesting (e.g. 'funky') natural coffees; and others prefer the cleaner, and usually more balanced characteristics of washed coffees. Dry-processing can offer taste experiences not found in washed coffees, such as distinct fruit and floral notes, although sometimes these characteristics are considered to make a coffee unbalanced and even faulty.

The extra steps involved in washing also mean that wet-processed coffees usually have fewer cupping defects. For example, unripe beans float in the fermentation tanks and can be removed easily, although this step can also be applied to dry-processed coffees. Generally, if dry-processed coffees are processed to a high standard, then they can match washed coffees in terms of quality and consistency.

One consideration for the consumer is that dry-processed coffees are more environmentally friendly, as the processing requires far less equipment, less fuel (for the de-pulping machinery) and most importantly little or no water. These factors make dry-processed coffee more carbon efficient, an important consideration as global coffee production produces a significant carbon footprint. In general, agriculture is a significant contributor to greenhouse gasses. Moreover, there can be some serious pollution issues resulting from wet mill run-off into streams and rivers, although properly implemented settling tanks (where waste water is stored and dispersed, rather than being released directly into the rivers) are helping to reduce this negative impact. Dry-processed coffee represents around 80% of total Ethiopian coffee production, although washed coffee is definitely on the increase, particularly following large-scale investment in the main coffee-growing areas.

Other processes (pulped natural and honey process)

Pulped natural and honey processing represent relatively new developments in coffee processing, and are undertaken to produce high-quality, speciality coffees. Pulped natural and honey processing are very similar. After the de-pulping stage, as for washed coffee (see above), the sticky parchment coffee is either given a quick rinse or not, but importantly the fermentation stage is omitted. Thus, when the de-pulped coffee is laid out on the drying beds it can still be covered in the plentiful remains of the pulp (mucilage), depending on the level of de-pulping and subsequent washing. Once on the drying beds, it is dried in a similar way to washed coffee. The honey process differs from pulped natural by the increased amount of pulp that is left on the parchment, which is controlled mainly by the amount of water that is used. On the drying bed, both types are instantly recognisable by the light to golden brown dried, sweet, sticky coating on the parchment (more so in the honey process). The coating (dried mucilage) contains high levels of sugars. The coffee is fully dried with the coating in place, again similar to fully washed coffee. The dried mucilage is only removed at the hulling stage, along with the parchment. Processing the coffee in this way adds sweetness and specific flavour characteristics, and if done correctly

produces sweet-tasting, interesting coffees, with qualities that usually set them apart from natural or washed coffees. Varying the amount of mucilage left on the parchment influences the characteristics of the coffee. Pulped natural and honey-process coffee is not common in Ethiopia, but production is underway on specific farms and cooperatives.

There are still a large number of other factors that influence quality and taste, even after the green coffee has been through most of the processing steps. These factors include pre-shipping processes (e.g. cleaning, sorting and grading), storage, and transportation; and, of course, in the country of consumption, the way the coffee is roasted, made and served, also has a considerable influence.

Resting

After drying, both natural (dry) and washed (wet) processed coffees require a 'resting' period. For dry processed coffees this is undertaken after the cherry has been properly dried, and for wet processed coffee at the dried parchment stage. The resting step lasts for 1–3 months, preferably in a properly ventilated warehouse or other suitable storage facility. In the case of small-scale farmers, the coffee is often rested in the smallholder's house or outbuilding. Resting or 'maturation' is undertaken to improve cup and transportation quality, but the exact duration can be more influenced by transport and processing logistics rather than careful timing. Sometimes the coffee is stored for longer periods, such as more than 6 months, but then the coffee starts to 'age' and will develop different flavour characteristics. If the moisture levels of the stored coffee are too high, or if there are other negative influences (heat, proximity to strong odours, or extended storage), the coffee will develop negative qualities (faults). In some countries coffee is aged intentionally to develop specific flavour characteristics, but this is not the case in Ethiopia.

Hulling

After drying, both dry- and wet-processed coffees need to be hulled. For dry-processed coffees the hard, blackened part (the husk, which was once the fleshy pulp of the fruit) has to be removed. For wet-processed coffee the parchment is removed by hulling (sometimes referred to as milling). Hulling is a mechanical process, performed using a machine of various manufacture, and usually driven by a petrol or electric motor. The facility that undertakes hulling is usually called the milling station. The hulling machines rub off the husk, and/or parchment, leaving clean, green coffee. After hulling the coffee may undergo sorting to remove defective beans and foreign material, especially for dry-processed coffees, and this is usually done by hand. Traditionally, hulling of coffee for household use was undertaken using a large, wooden pestle and mortar, and this method still persists in Ethiopia. Industrial hulling processes produce a lot of waste, especially for dry-processed coffees. The waste can be used for agricultural purposes, such as mulch and soil conditioner. In most Ethiopian milling stations, however, hulling by-products produced from dry-processed coffee are left to form large heaps next to the milling station, which eventually decompose and, due to the heat produced during decomposition, smoulder away for many weeks or months.

Green coffee

Green coffee represents the state at which coffee is exported to the consuming countries, for roasting, packaging, distribution and consumption. A large proportion of green coffee is not exported, however, and is roasted in Ethiopia, by the householder for home consumption and commercially for the domestic market.

Green coffee can be various shades of green, including bluish green to blue-green, which is often considered the best quality,



Coffee hulling station

Image: Jenny Williams

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Green coffee, after hulling Image: Jenny Williams

through to greyish blue, green or greenish, to almost white/very light brown (lowest quality)[49]. In the pre-export grading system (see below) the beans may also be referred to as faded, or blackened, and both represent faults in the coffee. Faded beans are soft and have a light brown, whitish brown, grey, or pale brown-green colour. The causes of faded beans are various, including over- or under-drying, poor storage (e.g. high humidity, high temperatures), or over-storage (kept too long in the storage facility). Blackened beans are brown to black in colour, and may be caused by drought, late-harvesting (over-mature), or over-fermentation during wet-processing. Other green coffee defects include 'cuts' (caused by suboptimal adjustment of the depulper, for washed coffees), insect damage (holes in beans), and a shrunken appearance or an irregular shape (often a sign of drought).

When green coffee reaches the delivery centres or warehouses it may undergo further sorting and cleaning, either using machinery (a colour sorter or airflow machine) or in many cases by hand and eye, to remove any hulling remains, foreign particles, and defective beans. In some cases further milling may take place to further clean the coffee. The green beans are also size-graded using a series of grids or sieves.

Speciality coffee

Speciality coffee is a classification given to high-quality coffee, which must be able to pass very specific physical grading criteria and sensory (aroma and taste) evaluation tests (cupping). The Speciality Coffee Association (SCA) defines speciality coffee in its green (unroasted) stage as: '…coffee that is free of primary defects, has no 'quakers' [an unripe and often bad-tasting coffee bean], is properly sized and dried, presents in the cup free of faults and taints and has distinctive attributes'. A speciality coffee should also be naturally sweet, and possess interesting flavour characteristics. To evaluate coffee, the SCA uses a standard international Quality Score. Only coffees with 80 or more points (out of 100) can be classified as speciality coffee. Coffees with a score close to, or above 90, are exceptional.

Grading

Before export all coffee must be graded. The Ethiopian Commodity Exchange (ECX) undertakes grading prior to accepting coffees for storage in its warehouses, where they are stored until sold through an auction system. The coffee grading system is strict and is based solely on quality. There are nine grades, covering both unwashed (natural or dry-processed) and washed (wet-processed) coffees, from Grade 1 (highest quality) to Grade 9 (lower), and ungraded (lowest). Grades 1 to 2 represent speciality coffee grade, i.e. the highest quality coffee to be exported to high-end roasters who will be selling their coffee at premium prices (see above). Grades 3 to 9 are export-quality coffees, and ungraded coffee stays in Ethiopia for the home market. Even though unwashed coffees are sometimes considered to be of lower quality, they can, and often are, placed in grades 1 and 2, as speciality coffees. The grading system follows the Coffee Quality Institute (CQI) system, which uses the combined result of (1) physical features (raw value) of the green coffee, and (2) cup quality or liquor characteristics (cup value). For washed (wet-processed coffees) the raw value is 40% of the grade and is made up of defects (20%), shape (10%), colour (5%), and odour (5%); cup value accounts for 60% is made up of cleanness (15%), acidity (15%), body (15%), and flavour (15%). Cup defects (such as taints and bad taste characteristics) are marked in the cleanness section of the grading system. For unwashed (natural or dry-processed) coffees: the raw value accounts for 40% of the score and is made up of defects (30%) and odour (10%); cup value (60%) is assessed in the same way as for wet-processed coffees. In addition, the quality evaluation includes an assessment of green bean moisture levels. Typically, beans with greater than 12% or below 9% moisture levels are rejected.

Coffee processors, buyers and exporters may also evaluate and grade their coffee before it is taken to Ethiopian Commodity Exchange (ECX) warehouses, or prior to direct export via co-operatives or other means.

The trading system and coffee classification

There are various ways that processed (and unprocessed) coffee is traded within Ethiopia before reaching the central trading system (see below). Processed coffee (and fresh cherry) can be taken to the local market or sold to cooperatives or coffee middlemen (*akrabis*). Generally, coffee exporters buy green coffee from the larger-scale regional suppliers, including the cooperatives, through the Ethiopian Commodity Exchange (ECX) auction system (as part of the regulatory requirement for in-country coffee transactions), although limited exportation from cooperatives and other producers may go through other routes. The ECX auction system is strictly organised in order to ensure that in-country value-chain steps are controlled, and are measurable and traceable. For example, there is a regulatory requirement forbidding trade or movement of coffee from one coffee-growing region to another. All regional coffee producers and suppliers are required to deliver their coffee directly to the dedicated ECX station within their coffee-growing area[50],

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where the coffee is stored until it is transported to ECX's national coffee exchange market in Addis Ababa. This allows traceability of origin, at least to one of the major coffee-growing areas, or a specific larger-scale origin (e.g. Yirgacheffe, Guji). This system is enforced by check-points on major roads, and by origin and quality inspection at various stages of the transportation and transaction process, including checks by government officials. One of the key activities for quality control is grading, which is undertaken by the ECX at the federal and national level (see above).

In order to organise and manage the traceability of the various origins, the Ethiopian Commodity Exchange (ECX) has devised its own coffee classification system, based on geographical growing areas and their cup profiles, factoring-in the main processing types (i.e. natural/dry vs. washed/wet-processed) and grading. This classification system[50] provides a framework for a number of logistic processes, and allows traceability should the exporter or buyer want to know the area from where the coffee was grown (origin). As an origin is often linked to a specific cup profile, the coffee buyer or consumer will know what to expect from any particular coffee, and may select an origin to suit one or a number of purposes. For many, however, and particularly for speciality coffee buyers, this system does not provide sufficient traceability: coffee from numerous farms, and from across more than one origin, can be combined into a single lot, for example. The ECX system has undergone significant change over the past few years, and further changes are likely in the future.

Exportation

After all processing and post processing steps have been completed, the coffee is weighed and packed into 60 kg food-grade jute sacks, or is bulk-containerised into a lined shipping container. A single 20 ft shipping container holds 18,000 kg (18 metric tonnes (MT)) of coffee in 300 × 60 kg sacks; or when loose and un-bagged, 19,000 kgs (19 MT). From Addis Ababa, coffee loads are transported by road or rail to the Port of Djibouti, where they are delivered to the designated shipping carrier for export via either the Gulf of Aden or the Red Sea. The time taken from harvest to delivery at the buyer's warehouse in the destination country can be lengthy. Coffee harvested in Ethiopia in November might take 9–10 months to reach the docks in the United Kingdom, and thus not reaching its destination until July or August the following year, for example.



Sorting green coffee by hand (Yayu, Illubabor coffee area, south-west Ethiopia)

Image: Jenny Williams

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Wild coffee forest near Bonga
Image: Jenny Williams

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10. The coffee areas

Overview

The coffee landscape of Ethiopia is organised here into five zones, and 16 areas (Table 1, Figure 7). The main coffee-growing areas are found within the Oromia Region and the Southern Nations, Nationalities, and Peoples' Region (SNNPR), with modest production in the Amhara Region and minor output in the Benishangul Gumuz Region (Figure 7). The five coffee zones are: North, South West, Rift, South East and Harar. The greater part of coffee production in Ethiopia is from the largely forested South West coffee zone, followed by the Sidamo (including Yirgacheffe) coffee area of the South East coffee zone. Harar was once an important producing zone but has declined considerably since the 1960s, and possibly some decades before. The other coffee zones (Rift and North) are modest producers compared to the South West coffee zone and Sidamo coffee area.

The 16 coffee areas (Table 1) are based on modelled coffee (niche) suitability and forest cover (from satellite data; see Chapter 2), incorporating common conventions and terminology from the coffee sector, and terminology adapted from the Ethiopian Commodity Exchange (ECX) contract system[50]. It was not possible to follow the ECX system precisely, as the designation of the ECX geographical nomenclature also depends on the method of processing (e.g. washed vs. unwashed; speciality vs. commodity), and is thus not strictly aligned with geographical distribution. Moreover, the ECX contracts may change from year-to-year. Table 1 provides a summary of the 16 coffee areas, indicating the general position within Ethiopia (relative to the Rift Valley), their assigned coffee zone, and the administrative region in which each coffee area is situated. Figure 7 shows the geographical position of the coffee zones and coffee areas. Figure 6 (page 29) summarises the present-day suitability for coffee-growing and recent forest change. The Atlas map pages (1–41) show the suitability for coffee farming, in relation to forest and non-forest cover, in detail.

In the section below we provide a short narrative for each of the coffee zones and their coffee areas, giving basic location details and an overview of the main production systems and their characteristics.

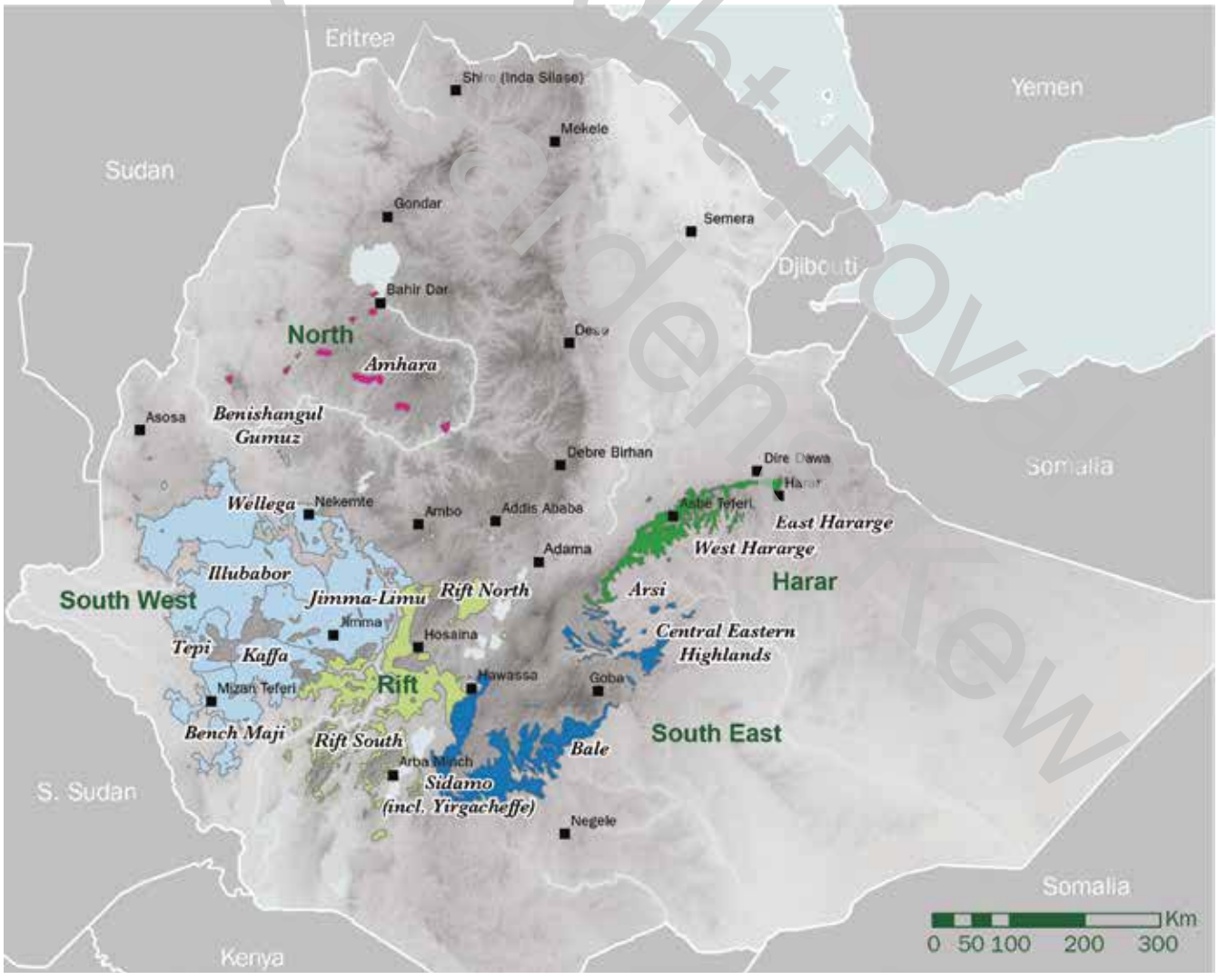


Figure 7. The coffee-growing zones (North, South West, Rift, South East, Harar) and coffee areas (in italics) of Ethiopia. See Table 1, on page 50.

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Position in Ethiopia	Main coffee zone	Coffee area	Region (administrative)
A. West of Rift Valley	A1. North	A1.1 Amhara	Amhara
		A1.2 Benishangul Gumuz	Benishangul Gumuz
	A2. South West	A2.1 Wellega	Oromia
		A2.2 Illubabor	Oromia
		A2.3 Jimma-Limu	Oromia
		A2.4 Tepi	SNNPR and Gambella*
		A2.5 Kaffa	SNNPR
		A2.6 Bench Maji	SNNPR
B. Rift Valley	B1. Rift	B1.1 Rift North	SNNPR and Oromia*
		B1.2 Rift South	SNNPR
C. East of Rift Valley	C1. South East	C1.1 Sidamo (incl. Yirgacheffe)	SNNPR and Oromia*
		C1.2 Bale	Oromia
		C1.3 Central Eastern Highlands	Oromia
	C2. Harar	C2.1 Arsi	Oromia
		C2.2 West Hararge	Oromia
		C2.3 East Hararge	Oromia

Table 1. Main coffee zones and coffee areas and their position within Ethiopia. See Figure 7, page 49.

Notes: *Only a minor part of this region is within this coffee area. SNNPR = Southern Nations, Nationalities, and Peoples' Region.

A. West of the Rift Valley

A1. North Zone

This is a minor coffee zone, with isolated areas of coffee production. It is divided into two coffee areas: Amhara and Benishangul Gumuz, each of which sits within their respective administrative regional boundaries (Table 1). Generally, the climate in the Amhara and Benishangul Gumuz regions is too dry for coffee (the wet season is shorter than that in the south-west), but where there is sufficient water for irrigation and/or land available at higher elevations, coffee is grown successfully. Most of the coffee in the North coffee zone is shade coffee. Arabica coffee is not wild (indigenous) in this zone.

A1.1 Amhara (Atlas map pages 26, 27, 33, 34)

The Amhara coffee area starts around the town of Debre Markos, where coffee gardens are the predominant production system. Farms around the town of Finote Selam contribute significantly to the coffee production of the Amhara coffee area. The high water table and presence of rivers and streams in and around Finote Selam enables irrigation, and there are some sizeable farms dedicated to irrigated production. Further north there is small- to medium-scale coffee production between the towns of Injibara and Chagni, with coffee being grown both with and without irrigation. Throughout this area, where conditions are suitable, there are numerous small coffee gardens. Zege (Zeghie) Peninsula (1,800–1,950 m), on the south-western edge of Lake Tana, is a small patch of humid forest that has been producing coffee for at least the past two centuries. Many hundreds of small-holders produce semi-forest coffee (SFC) at Zege, but good harvests are infrequent. Coffee is not indigenous to Zege, but is believed to have been brought from south-west Ethiopia 200–300 years ago. The locals consider their coffee to be milder than that coming from south-west Ethiopia, with some referring to it as *Zege buna*.

Zege is often considered the most northern limit for coffee in Ethiopia, although there are isolated coffee gardens north of Bahir Dar. Historical records from the eighteenth and early nineteenth centuries report limited coffee cultivation (probably coffee gardens) from Gonder (Amhara Region) and the Tigray Region. Coffee-growing in the Amhara Region is generally restricted to 1,700–2,200 m, although new coffee production areas are being established at elevations in excess of 2,400 m. Production is largely restricted to natural (dry) processing, with isolated washing stations. Amhara coffees usually have light acidity and light to medium body, with notes of red berries and citrus; Zege coffee can have interesting fermented fruit characteristics, with notes of port, sherry and whisky.

A1.2 Benishangul Gumuz (Atlas map page 25)

Benishangul Gumuz is the smallest and most isolated of all the coffee areas, and is restricted to a small high plateau at Debre Zeyit (Wembera). Coffee farming occurs on the western side of the plateau, west of Debre Zeyit town, at 1,700–2,200 m. Coffee growing at this location is mostly above 1,800 m, on steep slopes, and of the forest garden coffee (FGC) type, with irrigation used where water is available. Coffee from this area is not well known, and mostly not exported. The coffee is dry-processed, and covers low to high grades. Coffee from Debre Zeyit has some excellent qualities (silky body, notes of citrus, various fruits and tropical flowers, and good sweetness). The positive attributes are assisted by high elevation, irrigation and good-quality harvesting. Coffee is not indigenous to this area and the plants used in this area probably originate from Wellega or Jimma-Limu coffee areas.

A2. South West Zone

The South West is the main coffee-producing zone of Ethiopia, located on the western side of the Rift Valley, on the massive highland plateau in the south-western part of the country (Figure 8, page 61). The South West coffee zone includes the famous coffee localities of Bonga, Kaffa and Limu, as well as the well-known coffee town and delivery centre of Jimma. The forests of the south-west are home to the largest populations of wild (indigenous) Arabica coffee. The South West zone is divided into six coffee areas: Wellega, Illubabor, Jimma-Limu, Tepi, Kaffa, and Bench Maji.

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A2.1 Wellega (Atlas map pages 16–18, 25)

The Wellega coffee area can be subdivided into three smaller areas, from west to east: Kelem Wellega, West Wellega and East Wellega. Kelem Wellega is the western-most part of the area, and includes the towns of Dembi Dollo, Ashi (Sedi), Gidami and Mugi. Garigeda lies between Ashi and Gidami, and includes both forest coffee production areas and natural coffee forests (with wild Arabica coffee). The woreda name Anfilo (or Anfillo) is sometimes associated with coffee from this area. Kelem Wellega includes many very good coffee-growing localities, particularly those with good forest cover at 1,700–2,100 m; forest in this area continues upwards to much higher elevations (over 2,300 m). Kelem Wellega is not a well-known coffee origin but has the potential for high-quality (speciality) coffee, with some distinct and unusual flavour profiles. West Wellega includes the major town of Gimbi, and the smaller towns of Guliso and Alem Teferi, with much of the coffee-growing around these three towns at 1,300–1,700 m. The area comprises coffee gardens and small to large coffee farms, as well as some smaller-sized plantations. The coffee is grown in full sun, light shade or shade, and there are also small, isolated patches of forest coffee (mostly forest garden coffee (FGC)). East Wellega includes the large town of Nekemte, and is similar in its coffee cultivation characteristics to West Wellega but with less coffee production (the eastern part of Wellega is generally less suitable for coffee-growing).

The Wellega area produces washed and dry-processed coffees, covering all grades[50]. Coffee from the Wellega area is often referred to as Lekemti, Nekemti (after the town of Nekemte) or Gimbi, but it could originate from almost anywhere in the Wellega coffee area. The higher-grade coffees can be distinct, sometimes with honey, citrus, and floral notes, especially those from Kelem Wellega. Coffee from East and West Wellega, particularly those referred to as Lekemti, tends to have rather large, elongated beans.

A2.2 Illubabor (Atlas map pages 17, 18)

The Illubabor coffee area is positioned south of the Wellega coffee area and north of the Tepi, Kaffa and Jimma-Limu coffee areas. The major town of the area is Metu (or Mettu), with the large towns of Gore and Bedele to the west and east, respectively. The Illubabor area extends some considerable distance to the west, to the west of Gore towards Gambela, until the high plateau ends. The southern part continues south of Bedele, and includes coffee farms around the town of Gechi. Large parts of this area are forested, including the dedicated coffee forest reserve at Yayu. Yayu and other forests in the area are home to important populations of wild (indigenous) Arabica coffee, which (as in many other areas of Ethiopia) is used to provide planting stock for coffee production. The coffee produced in this area is mostly of the forest (FC) and semi-forest (SFC) coffee type, although there are some large and intensively planted and managed areas, including small plantations. Often overlooked by coffee buyers and consumers, this area has much to offer and is now producing some excellent washed and natural processed coffees, particularly at elevations at and above 1,500 m. The coffees are generally low in acidity and body and display notes of tropical fruit, stone fruit, chocolate, caramel, and vanilla.



Inspecting the coffee harvest (Debre Zeyit (Wembera), Benishangul Gumuz coffee area, north-western Ethiopia) Image: Aaron Davis

Within the ECX coffee system, Illubabor coffee mostly falls under the Limu (washed) and Jimma (unwashed) contracts.

A2.3 Jimma-Limu (Atlas map pages 10, 18, 19)

The Jimma-Limu coffee area is in the eastern part of the South West coffee zone, and is centred on the town (and coffee delivery centre) of Jimma. It can be subdivided into two parts: Jimma and Limu. The Jimma part includes areas north of Jimma town, through the towns of Yebu, Gembe, Agaro, Toba, and to Dembi and Yembero. To the south of Jimma, the area extends to Dedo. To the east of Jimma the area reaches Welkite, although this part of the area is largely dominated by scattered coffee gardens. The south-western part of the area includes the towns of Seka and Sembo, ending before the town of Shebe. The north-western part of the area extends up to the edge of the Illubabor coffee area, while the south-western part adjoins the Kaffa coffee area. There are important coffee-growing locations west and south-west of Agaro, and to the south around the towns of Beshash and Chira. The elevation range is 1,500–2,200 m and sometimes almost up to 2,300 m. The Limu part of the Jimma-Limu coffee area is located north-east of Jimma and east of Agaro, and includes the towns of Ambuye, Gent (Suntu) and Seka (en route to Atnago), at elevations of 1,700–2,100 m.

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Jimma-Limu is a large and important coffee-producing area. Most of the production is forest garden coffee (FGC), semi-forest coffee (SFC) and smaller plantations. Despite the close association between Limu and Jimma, the coffees from these two localities can vary considerably. Limu carries a reputation for producing the better coffees, possibly because of the larger number of washing stations and generally better climate, although Agaro (Jimma) also carries a deservedly high reputation. Washed coffee from Illubabor (see above), and further afield, is sometimes referred to and/or classified as Limu. This sometimes causes confusion, although the flavour profiles can be similar. Limu is noted for its washed coffees, and for dry-processed coffees of higher grades. The standard of agronomy and processing is good in many places, with some well-established larger farms. Limu coffee is renowned for its balance, sweetness, lightly spiced, pleasant wine-like characteristics, and light to medium body; some Limu coffees have distinct floral and stone fruit notes. Coffee from Agaro, which is in the Jimma part of the Jimma-Limu coffee area, also has good sweetness and subtleness, with notes of stone fruit (apricot, peach), citrus, and sweet-scented tropical flowers.

A2.4 Tepi (Atlas map pages 9, 17)

The Tepi (or Teppi) coffee area is positioned between the coffee areas of Illubabor and Bench Maji (Figure 7, page 49). It starts just north of Tepi, around Gecha, and reaches beyond Masha towards Gore, and to areas west and east (in the southern part of the area) of these towns. There is a considerable amount of high ground in the Tepi coffee area, especially between Gecha and Masha (2,000–2,600 m), although much of this ground is too high for coffee (above 2,200 m). In Tepi, coffee is mainly found at 1,700–2,100 m. Much of the area is still densely forested, with some important populations of wild Arabica coffee. The Tepi Coffee Plantation is located to the west and north-west of Tepi, and is the second-largest coffee plantation in Ethiopia, covering over 8,000 ha. The Tepi plantation covers elevations of 1,200–1,900 m, although the majority of the coffee is situated below 1,500 m. The coffee from this area is largely of the forest (FC), semi-forest (SFC) and plantation coffee (PC) production types. Tepi coffees often have low acidity, slight to medium body and a soft, balanced flavour.

A2.5 Kaffa (Atlas map pages 9, 10)

This famous coffee area, often said to be the 'home of coffee', is centred on the town of Bonga. To the west, this coffee area extends through the towns of Wushwush (the site of large tea plantations), Dara, and Dimbira, and ends around Wacha. To the east, the Kaffa coffee area reaches the town of Shebe. It also covers a large area north and south of Bonga, adjoining the Jimma-Limu coffee area to the north-east, and the Bench Maji and Tepi coffee areas to the west. The southern part includes the town and coffee-producing locality of Anderacha.



Harvesting coffee (Yayu, Illubabor coffee area, south-west Ethiopia)

Image: Alan Schaller (courtesy of Union Coffee)

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Young coffee plants dwarfed by forest trees (near Gore, Illubabor coffee area, south-west Ethiopia) Image: Aaron Davis

In many places, there are still substantial tracts of natural and semi-natural forest, much of which is used for semi-forest coffee (SFC) production. The Kaffa coffee area includes the large and globally important UNESCO Kaffa Biosphere Reserve, which aims to preserve the wild coffee forests and their wildlife, as well as the considerable natural genetic resources of wild and semi-wild Arabica coffee found there. The Kaffa area produces washed coffees, particularly around Bonga and Anderacha, as well as dry-processed coffees. The major coffee production systems are of the semi-forest (SFC) and forest garden coffee (FGC) type, as well as small plantations, over a wide elevation range of 1,300–2,200 m, with most coffee at 1,700–2,000 m. Kaffa coffee has a medium body and acidity, with a variety of different flavour profiles.

A2.6 Bench Maji (Atlas map pages 2, 9)

This area includes the town of Mizan Teferi (Mizan Aman). The south-eastern part of the Bench Maji coffee area encompasses Bebeka and Gura Ferda, and in the southern part it includes the famous coffee origin of Gesha (east of Jemu) and areas around the town of Maji, reaching the northern edge of the Omo National Park. Bench Maji is an area of considerable contrasts, from the highly managed coffee plantations of Bebeka (1,000–1,400 m), to the largely untouched forests of Gura Ferda (1,700–2,300 m). It also includes the remnant wild coffee forests of Gesha (1,800–2,000 m) and the isolated coffee forests of Maji (mostly above 2,000 m). In the southern part of the Bench Maji area, coffee cultivation is interspersed with lower-lying crop and pasture lands. There are some important populations of wild Arabica in the forested areas around Gura Ferda, Gesha and Maji, and also at Sheko (south-west of Tepi), a densely forested area that also produces forest (FC) and semi-forest coffee (SFC).

The main production systems of the Bench Maji area are forest garden coffee (FGC), semi-forest coffee (SFC), plantation coffee (PC), and garden coffee (GC). Bebeka is currently the largest coffee plantation in Ethiopia, covering around 10,000 ha, producing more than 2,000 metric tonnes of coffee, and employing about 5,000 workers. It produces Arabica coffee, some robusta coffee (*Coffea canephora*), and also fruit, spices and honey.

Washed coffees of speciality, and high to lower grades, are produced in Bebeka and other parts of Bench Maji. Dry-processed coffees are produced throughout the area, from speciality through to low grades (and under-grades)[50]. Gesha is the home of the world-famous Gesha (Geisha) coffee, and this origin is now starting to produce its own very high quality washed, semi-washed, and dry-processed coffees. Gesha (Geisha) coffee grown within and outside Ethiopia (e.g. in Panama) is noted for its outstanding aroma and flavour, with notes of jasmine, black tea, and tropical fruit, and for profound sweetness. For these reasons, Gesha (Geisha) coffee is sought-after and usually commands a high price. The flavour profiles across Bench Maji are variable.

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B. Rift Valley

B1. Rift Zone

The Rift coffee zone is located between the main south-western plateau and the Sidamo coffee area (Figure 7, page 49). Coffee is grown where conditions are wet and cool enough, at suitably high elevations above the low lying (and considerably warmer and drier) lands of the Rift Valley. The coffee landscape here is dominated by garden coffee (GC) and coffee cultivation in small, mixed-cropping systems. The Rift Valley is not a major producing area, and is largely devoid of forest. It is divided into two parts: Rift North and Rift South. Coffee from the Rift falls within the Sidamo C and Sidamo E contract system of the ECX, with Soddo as the coffee delivery centre. The Rift Valley coffee zone produces mainly, but not exclusively, dry-processed coffee. Bean size and shape is variable but tends to be small, rather rounded and hard (dense), especially for beans grown in the Rift South coffee area, and is thus similar physically to Yemen Mocha (Mocca) coffee. The physical characteristics of the beans are probably due to climatic factors, particularly lower rainfall and higher temperatures.

B1.1 Rift North (Atlas map pages 11, 19, 20)

Soddo is the main town of the Rift North coffee area. Coffee-growing here is fragmented and spread over a large area, with moderate to high concentrations of garden coffee (GC) around the towns of Durame and Angecha (north of Soddo) and Tulema and Waka (west of Soddo), in locations south of Welkite, and in the northern-most part of the area around Butajira. The coffee-growing areas are largely confined to elevations of 1,800–2,200 m.

B1.2 Rift South (Atlas map pages 3, 4, 11)

The Rift South coffee area is located in the southern part of Ethiopia's coffee landscape, south and west of Lake Abaya. Arba Minch is the principal town in this area. As in the Rift North area, coffee is confined to higher elevations (1,700–2,200 m), for example to the west (Jinka, Wib Hamer, and Bulki (Bulchi)) and south (around Gidole) of Arba Minch.

C. East of the Rift Valley

C1. South East Zone

The South East is a major coffee zone, located on the eastern side of the Rift Valley. The zone incudes the well-known Sidamo coffee area, and the famous coffee town of Yirgacheffe. The zone is divided into three coffee areas: Sidamo, Bale, and the Central Eastern Highlands. Most of the production in the South East zone is confined to Sidamo, particularly the western part, with far less coffee farming in Bale, and only minor production in the Central Eastern Highlands. The eastern part of the Sidamo coffee area includes many of the lesser-known coffee origins, such as Bensa, Bona Zuria, and West Arsi (Nansebo) and Guji, although Guji has recently, and quickly, earned a reputation for interesting, high-quality coffee.

C1.1 Sidamo (including Yirgacheffe) (Atlas pages 4, 5, 11, 12)

The well-known Sidamo (or Sidama) coffee area of south-east Ethiopia includes the equally renowned coffee locality Yirgacheffe (Yirga Chefe). Sidamo is a major coffee-producing area, and encompasses an incredibly diverse range of flavour



Semi-forest coffee production (Harenna Forest, Bale coffee area, south-east Ethiopia) Image: Aaron Davis

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profiles. The main part of the Sidamo coffee area is narrow and discrete, running along a broad rift, north to south, from Hawassa (Awassa) to Gedeb (just south of Yirgacheffe). The northern part of this main area includes the towns (from north to south) of Wendo Genet, Yirga Alem and Aleta Wendo. In this part of Sidamo, Hawassa is the main coffee delivery centre. In the southern part of the main Sidamo area, Dilla is the main town and coffee delivery centre. Towns include (from north to south) Wenago, Koti, Yirgacheffe and Fiseha Genet (Abel). Under the ECX contract system, coffees from this western part of the area mostly fall under Sidamo B and Yirgacheffe A/B, although there are also other ECX classifications linked to origin (e.g. Wenago, Kochere, Wonsho). Small villages around Yirgacheffe are also sometimes listed as specific coffee-producing origins.

Beyond the main western part of the Sidamo coffee area, eastern Sidamo extends into the western part of the Bale Mountains. The road from Aleta Wendo, through Bore, Kibre Mengist, Zembaba Wiha, to Wadera, cuts through the south-eastern part of Sidamo. Further north (Atlas map pages 5 and 12), there are three lesser-known coffee localities: Bona Zuria, Bensa, and West Arsi (Nansebo). West Arsi (Nansebo) produces high-quality washed and natural coffees, at high elevations (1,800–2,300 m), based close to the town of Bulega. Under the ECX classification, coffees from this part of Sidamo usually fall under Sidamo A. In the most southern part of the Sidamo coffee area is the coffee locality of Guji, which extends over a considerable area and includes higher-elevation coffee-growing areas. The principal towns of this area are Agere Mariyam and Kercha (see Atlas map pages 4 and 5), with most of the production occurring in isolated localities at higher elevations of 1,900–2,300 m, including some larger farms.

Coffee farming in the western part of the Sidamo coffee area ranges in elevation from 1,600 m to 2,100 m, and in the eastern part 1,700–2,200 m, and sometimes as high as 2,300 m. The western part of the Sidamo coffee area is set apart from the rest of the Ethiopian coffee landscape by its distinctive cultivation system. Families in this area farm small and intensively managed mixed crops in association with forest trees or other canopy trees or vegetation, in a system known as agroforestry. The individual plots are typically a quarter to half a hectare and feature coffee, the starch staple (and banana-like) enset (*Ensete ventricosum*), yams (various species of *Dioscorea*) and eucalyptus (various species of *Eucalyptus*) among the main crop species. Some parts of Sidamo look heavily forested, until closer inspection reveals an intensive and productive agroforestry system. In other parts of the Sidamo coffee area, particularly north of Yirga Alem and Aposto, the cultivation system is more open, and either lightly shaded or in full sun.

The Sidamo coffee area produces washed and dry-processed coffees, with recent years seeing a large increase in the number of washing stations. Sidamo and Yirgacheffe coffees are noted for their extremely distinctive, often very fruity, floral and citrus flavour profiles. Most Yirgacheffe coffees have a particularly unique and distinctive flavour profile, with intense fruit, nuts, citrus, chocolate and almost perfume-like qualities, which is often referred to as the 'Yirgacheffe flavour'. Guji coffee is generally not well known but is quickly gaining a reputation for delicious, high-quality coffees (washed and natural), with notes of sweet citrus, floral, tea, rose, and various fruits, but especially vibrant, juicy blueberry. Even less well known are the coffees from Bona Zuria, Bensa and West Arsi (Nansebo). West Arsi (Nansebo) is now more evident in the speciality coffee market; the washed versions possess good balance, bright acidity and smooth mouthfeel, with notes of black tea, bright citrus, and floral aromas (e.g. cherry blossom).

C1.2 Bale (Atlas map pages 5, 6, 12, 13)

The Bale coffee area is situated in the southern part of the Bale Mountains, which have peaks of just over 4,300 m and a plateau area (Sanetti Plateau) with an average elevation of 4,000 m. Coffee is not farmed at these high elevations but within the Harenna Forest and adjoining forest areas. Here we find humid, evergreen forest of the same general type as that found in south-western Ethiopia (i.e. Moist evergreen Afromontane forest (MAF)[5]. Harenna forest is home to wild Arabica coffee, and it is these plants that are used to produce coffee, mostly of the forest (FC) and semi-forest (SFC) production types, but also forest garden coffee (FGC). Around 9,000 households are engaged in coffee production in Harenna Forest. Even though the forest extends up to 2,300 m, coffee production is confined to a belt from 1,400 m, where the humid forest starts, to around 1,800 m, the upper limit being restricted by low temperatures. The town of Mena (Dolo Mena) lies to the south of the main forest area.

The Bale coffee area is poorly known as a coffee origin, possibly because access was difficult until quite recently. Coffee from Bale is physically similar to some of the Harar coffees, with a large, long-oblong bean. Bale coffee has a distinctive flavour profile, including notes of floral, fruit, vanilla and sweet nuts. Bale coffee can be outstanding, although more investment is required to make the best of this potentially exceptional coffee. All of the coffee is dry-processed, and classified as Bale under the ECX contract system.

C1.3 Central Eastern Highlands (Atlas map pages 12, 13, 14)

This coffee area is situated south of the Arsi coffee area (Harar zone) and north of the Bale coffee area. The main towns of this area include Seru, Gaser, Ginir, Jara and Sheki Husen. The Central Eastern Highlands is a minor coffee area, largely comprising garden coffee (GC), grown under slight shade or in full sun. Coffee production occurs over a large area here, but production is slight compared to that of the Sidamo coffee area, with the majority of production for home use and the local market. Coffee from this area is dry-processed.

C2. Harar Zone

This well-known coffee origin sits on the north-eastern side of the Rift Valley, and runs along a mountainous ridge stretching from Chole (south-east of Adama (Nazret)) to the legendary city of Harar. The coffee-growing climate here is drier, and sometimes cooler, than that of the rest of Ethiopia's coffee landscape and, like the coffee-growing areas on the eastern side of the Rift Valley, has a bimodal rainfall pattern (see

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Coffee-growing in the Harar coffee zone (Arsi coffee area, eastern-central Ethiopia) Image: Aaron Davis

Chapter 6). The natural vegetation is different to those of most of the other coffee areas, and is characterised by a drier type of vegetation, dominated by evergreen trees or shrubs, and common native coniferous species (classified as Dry evergreen Afromontane forest (DAF))[5]. Much of the coffee is grown without shade (sun coffee), or with minimal shade, mostly in coffee gardens (garden coffee (GC)), as part of a mixed cropping system. Some of the coffee in Harar is grown in terraces, and where there is access to water it may be irrigated.

The coffee from Harar is mostly dry-processed, although there are isolated washing stations. Harar coffees often have a distinct jam-like flavour, with a characteristic blueberry note (with some stone fruit and spice). They are medium to heavy in body and with moderate to good acidity. Although there are many heirloom cultivars in Harar, two common bean types are often recognised: Harar longberry, a coffee with a rather large, elongated bean; and Amber coffee, which has an amber-coloured bean, believed to be caused by specific soil conditions. Harar coffee is much sought-after but there are often issues with quality. There is a long-standing tradition in Harar of drinking tea made from the leaves of coffee, and also of using the fleshy part of the coffee fruit to make hot and cold beverages.

There has been a decline in the production of Harar coffee, possibly as a result of climate-induced stress, although conversion to production of the narcotic khat (*Catha edulis*) has probably had a stronger influence on this decline. Since at least the 1960s, farmers have moved to growing this more lucrative crop at the expense of coffee farming and best-practice coffee agronomy.

Harar is divided into three coffee areas, from west to east: Arsi, West Hararge, and East Hararge. Under the ECX contract system, coffees from these areas are classified as Harar A, B and C, depending on their origin and whether they belong to either speciality or commercial grades. Dire Dawa, a large commercial town, is the ECX delivery centre (East Hararge), and a key node for the transportation of Ethiopian coffee to Djibouti.

C2.1 Arsi (Atlas map page 21)

The Arsi (Harar C) coffee area starts at the base of the escarpment at its most western and southern edge, around Chole (south-east of Adama (Nazret)). Towns include Gololcha, and Mechara, with coffee grown at elevations of 1,500–2,000 m. The more successful coffee farms are located above 1,700 m, and use terracing and some shade provided by indigenous trees. In the southern part of Arsi, there is a large shade coffee plantation at Gololcha, which is partly irrigated.

C2.2 West Hararge (Atlas map pages 21, 22)

The West Hararge (Harar B and A) coffee area forms the middle section of the Harar coffee zone, starting north of Mechara and continuing through the towns of Gelemso, Asbe Teferi, Hirna and slightly beyond. Coffee is grown here at elevations of 1,700–2,200 m.

C2.3 East Hararge (Atlas map pages 22, 23, 30, 31)

The East Hararge (Harar A and B) coffee area starts around Kobo and Deder and reaches to the city of Harar, with the chartered city of Dire Dawa to the north. The elevation for coffee ranges from 1,900–2,200 m. On travelling through this coffee area, it appears that very little coffee is being grown. Much of the coffee is confined to suitable microclimates or where the water table is close to the surface, or where water is available for irrigation. There is also production south of Harawacha and around the towns of Bedeno and Girawa.

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12. Scope and use of Atlas

Coffee suitability

Two main categories are used in the Atlas for coffee (niche) suitability: Forest and Non-Forest. 'Forest' covers areas where there is indigenous forest or significant agroforestry present, and is divided into three colours depending on the suitability for coffee farming: Fair (green-grey), Good (light green) and Excellent (dark green). 'Non-forest' refers to areas where there is little or no forest but there is suitability for coffee farming: Fair (pink), Good (blue-grey) and Excellent (mauve). In most cases, shaded areas for forest (or significant agroforestry) indicate actual coffee-growing areas, although the intensity of farming will vary. Areas shaded for non-forest could grow coffee with suitable intervention (e.g. shade or improved shade cover from the planting of suitable indigenous shade trees) depending on the suitability category (Fair, Good or Excellent). Or, there may be non-forest coffee being farmed in these areas. The three coffee farming suitability categories are explained below. See also Key to Symbols on Atlas map page 1.

Fair. Coffee farming is possible and sometimes good, but may require additional inputs (e.g. irrigation, shade or improved shade). Yields poor in years with low rainfall and high temperatures.

Good. Coffee farming good, with the potential for consistent, high-quality yields. Yield and quality may be negatively influenced in some years (by adverse weather conditions, especially low rainfall and high temperatures).

Excellent. Coffee farming good to excellent, with the potential for consistent, high-quality yields. Yields and quality can be negatively influenced by adverse weather conditions, but this is less likely than in other areas.

Figure 6 (page 29) provides summarised information for coffee farming suitability and forest cover; the Atlas maps show the coffee farming suitability in detail.

Wild coffee forests

Wild Arabica coffee is found in nearly all the forested areas with Excellent or Good coffee (niche) suitability, which is marked dark green on the Atlas maps, with the exception of most parts of the western Sidamo coffee area. Wild coffee forests occur in the western part of A2.1 Wellega (Kelem Wellega), A2.2 Illubabor, A2.3 Jimma-Limu, A2.4 Tepi, A2.5 Kaffa, A2.6 Bench Maji, and C1.2 Bale coffee areas (see Chapter 10 and Atlas map pages).

Other (non-coffee) humid forest

The grey shading on the maps mainly denotes humid forest of the Moist evergreen Afromontane forest (MAF) and Transitional rain forest (TRF)[5] types, but lacking (or currently lacking) suitability for coffee. Further information on these forest types is provided in Chapter 8 (Coffee farming). Humid forest occurs at elevations between 450 m and c. 3,000 m, and so can occur outside of the current elevation range for coffee suitability (900–2,300 m). Humid forest is now rare in Ethiopia below 900 m; lower elevation humid forest (450–900 m) is mainly restricted to western Ethiopia in the far western part of the Ethiopian coffee landscape (see Atlas map pages 8, 9, 16, 17). Higher elevation humid forest areas (e.g. above 2,300 m) may come into suitability as the climate warms[10].

Coffee gardens (coffee bean symbol)

The scale of coffee-growing in the coffee garden (garden coffee (GC)) areas ranges from a few trees to small plots (e.g. 10–50 coffee trees), to medium-sized plots (e.g. 100–500 trees). Yields may be poor and inconsistent, or good, largely depending on inputs (e.g. irrigation) and/or local conditions (e.g. microclimate or water table). Coffee gardens are mostly found in full sun or light shade, and often close to households.

Other coffee information

Coffee zones and areas. Coffee zones and coffee areas are listed, mapped, and described in Chapter 10 (The Coffee Areas).

Coffee localities. The symbol (an upright Ethiopian coffee pot (jebena)) denotes a significant or valuable coffee-growing locality (origin), associated with the coffee that is growing there (e.g. Limu, Kaffa, Bale). Some lesser-known localities have been included to better detail the coffee farming landscape, including those at the extremities (e.g. Konso, Zege) and in isolated places (e.g. Debre Zeyit) within the coffee-growing landscape of Ethiopia.

Coffee towns. The symbol (a tilted, pouring, Ethiopian coffee pot (jebena)) is used in a similar way as for coffee localities, but in this case the coffee locality is directly associated with the town's name (e.g. Agaro, Jimma, Bonga, Yirgacheffe). In fact, in some coffee towns, a large tilting coffee pot (jebena) is placed in the centre of town (e.g. in Jimma and Bonga).

Coffee delivery centres. The symbol of a factory building denotes an ECX coffee delivery centre, from where the surrounding region's coffee is delivered for the later stages of processing (e.g. hulling, grading, weighing) and ongoing transportation. The delivery centres represent key nodes in the logistic framework for Ethiopian coffee processing and transportation. Some delivery centres are also coffee towns (see above), for example Bonga and Jimma, whereas others are not (e.g. Dilla).

Other mapping information

Regions, zones, woredas and kebeles

Addis Ababa is the capital city of Ethiopia. Ethiopia is divided into a hierarchy of administrative divisions, including regions, chartered cities, zones, woredas and kebeles. There are nine regions (capital towns are given in parentheses): Afar (Semera), Amhara (Bahir Dar), Benishangul Gumuz (Asosa), Gambella (Gambela), Harari (Harar), Oromia (Addis Ababa/Finfinne), Somali (Jijiga/Jigjiga), Southern Nations, Nationalities, and Peoples' Region [SNNPR] (Hawassa) and Tigray (Mekele).

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Addis Ababa and Dire Dawa are the two chartered cities. The regions are subdivided into zones (second-level division), and are displayed in Figure 8 and on Atlas map page 1. Woredas (third-level subdivision) are generally subdivisions of zones, and each has its own elected council. Kebeles (fourth-level subdivision) are the smallest administrative unit and represent an administrative delimitation at the local level. The Atlas does not provide information at the level of Woreda and Kebele.

The names of zones, regions, woredas and kebeles are subject to change and regional variation, and it should be noted that those used in the Atlas are unlikely to precisely follow the most recent nomenclature and geographical boundaries.

Settlements, transport and navigation

Inevitably there will be some inaccuracies in the Atlas, due to outdated mapping data, especially for roads, settlements (regional capitals, towns and larger villages) and railways. In particular, many roads are being upgraded and new ones built (see below). For these reasons, the mapping data presented in the Atlas should not be relied upon for detailed, accurate navigation. A navigation disclaimer is given on page 3.

Settlements have been classified into three categories on the Atlas map pages: (1) regional capitals (upper case; e.g. GAMBELA); (2) major towns (bold; e.g. **Arba Minch**); and (3) other towns (non-bold; e.g. Alem Teferi). The last two of these categories (major towns and other towns) provide the user of the Atlas with an indication of size and amenities. Thus, for the traveller, major towns will normally have several restaurants, accommodation (hotel or other), at least one bank, and in many cases, at least one fuel/service station. Some of the larger towns will have an airport or airstrip (see Gazetteer). Major amenities are present in regional capitals.

We have done our best to update and classify the roads, but the Atlas cannot be relied upon for either accuracy or up-to-date information. Ethiopian roads are in a continual state of development, with upgrades, new routes, and some minor or little-used roads falling into disrepair. If in doubt it is always a good idea to ask locally for information on road condition and specific routes.

The Atlas includes the abandoned Addis Ababa to Djibouti railway, but not the recently completed electrified railway, for the same destinations. For most of its course, the new railway runs more or less alongside the older one.

A gazetteer (geographical name index) is provided on Atlas map pages 43–59, to enable the user to find zones, coffee-growing localities, coffee towns, coffee delivery centres, regional capitals, airports, protected areas (e.g. protected areas and wildlife reserves), major lakes, summits/mountains and towns/settlements.

The names of settlements (e.g. towns) are subject to change and regional variation.

Elevation and topology

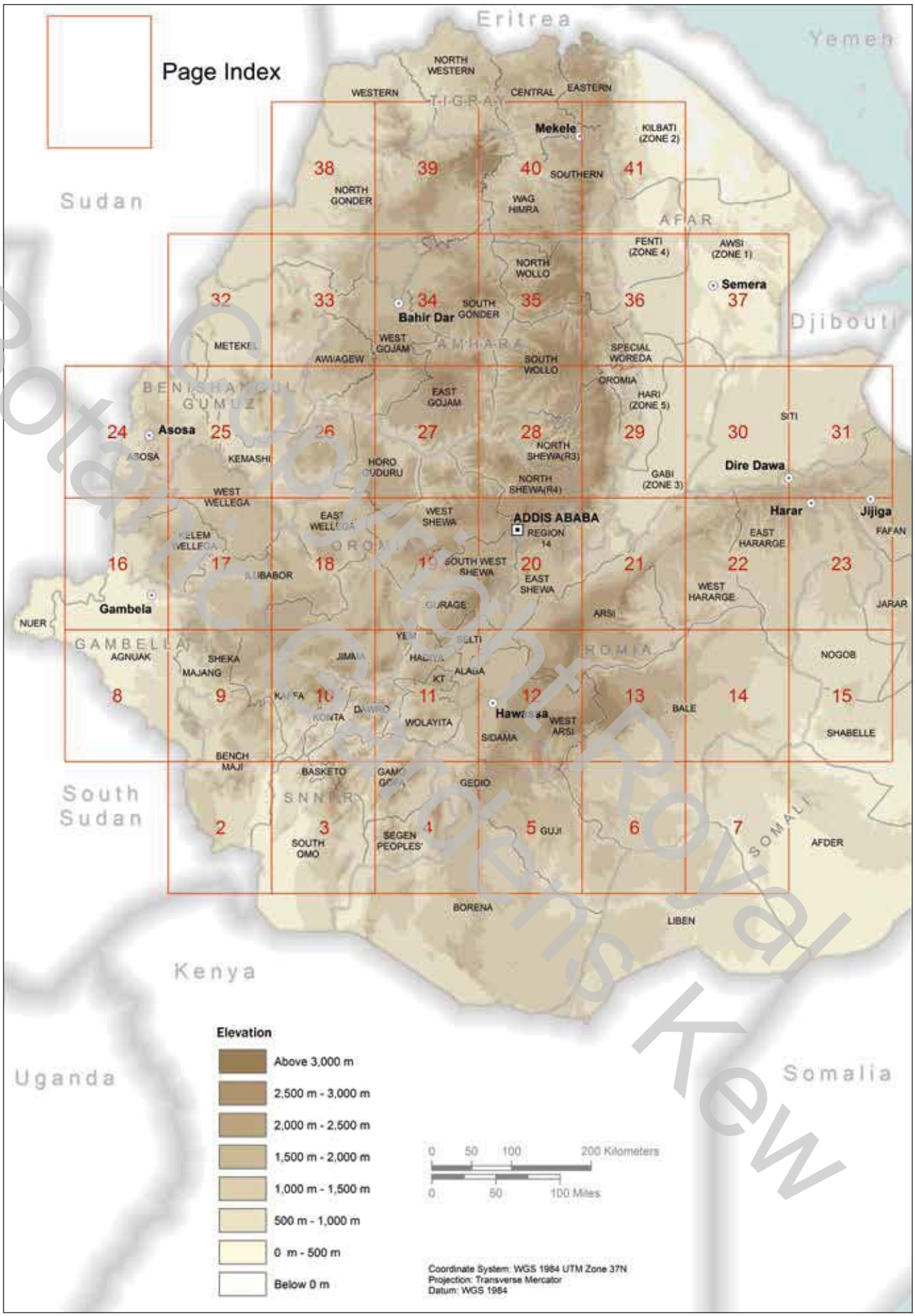
In order to portray the elevation and landscape encompassed by the Atlas, the Shuttle Radar Topography Mission (SRTM) digital elevation database[51] has been processed to produce a colour-shaded relief image map. The colouring corresponds directly to elevation, which when combined with the relief shading shows the topology in the Atlas map pages; major peaks (mountains) are named and indicated (with a triangle). Figure 8 represents an elevation map for the whole of Ethiopia, overlaid with the Atlas page index. This will enable to reader to gauge the approximate elevations for a given area or locality.



View across the Simien Mountains (North Gonder, Amhara)

Image: Jenny Williams

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Figure 8. Elevation map. Numbers refer to Atlas map page numbers. Regions are given in large upper-case, zones in smaller upper-case. The capital city (Addis Ababa) is indicated with a square bullet-point, and regional capitals are indicated with round bullet-points. KT = Kembata Tembaro (zone).



Serving traditional Ethiopian coffee
Image: Alan Schaller (courtesy of Union Coffee)

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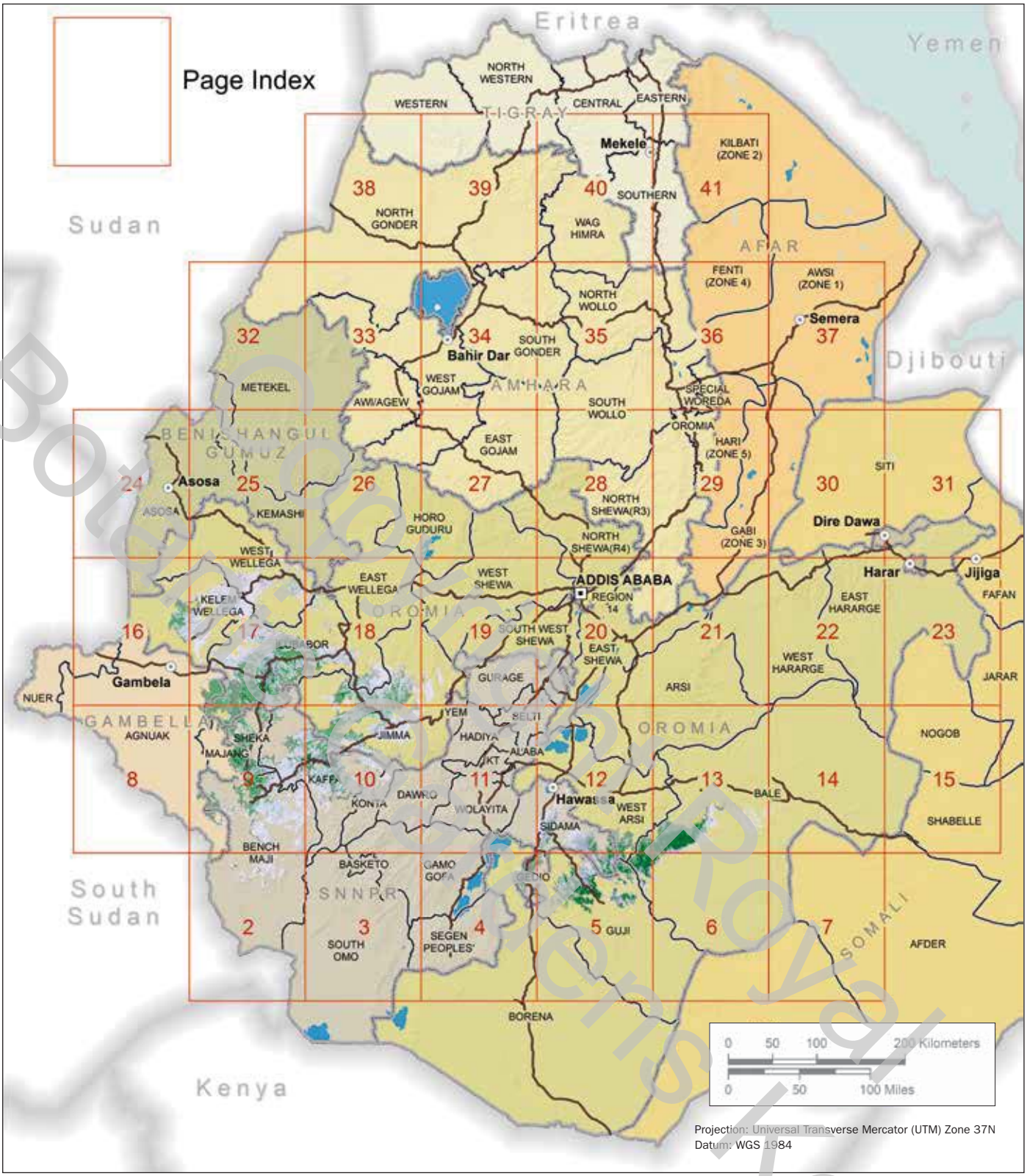
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Key to Symbols

PLACES
- Towns
- Airports
- Mountains and Peaks

ROADS AND RAIL
- Main road
- Secondary road
- Other road
- Railway

BORDERS
- State
- Region
- Zone

PROTECTED AREAS
- Protected areas

DRAINAGE

Rivers
- Principal river

Water bodies
- Permanent
- Seasonal

COFFEE SUITABILITY

i. Forest
- Fair
- Good
- Excellent

ii. Non-forest
- Fair
- Good
- Excellent

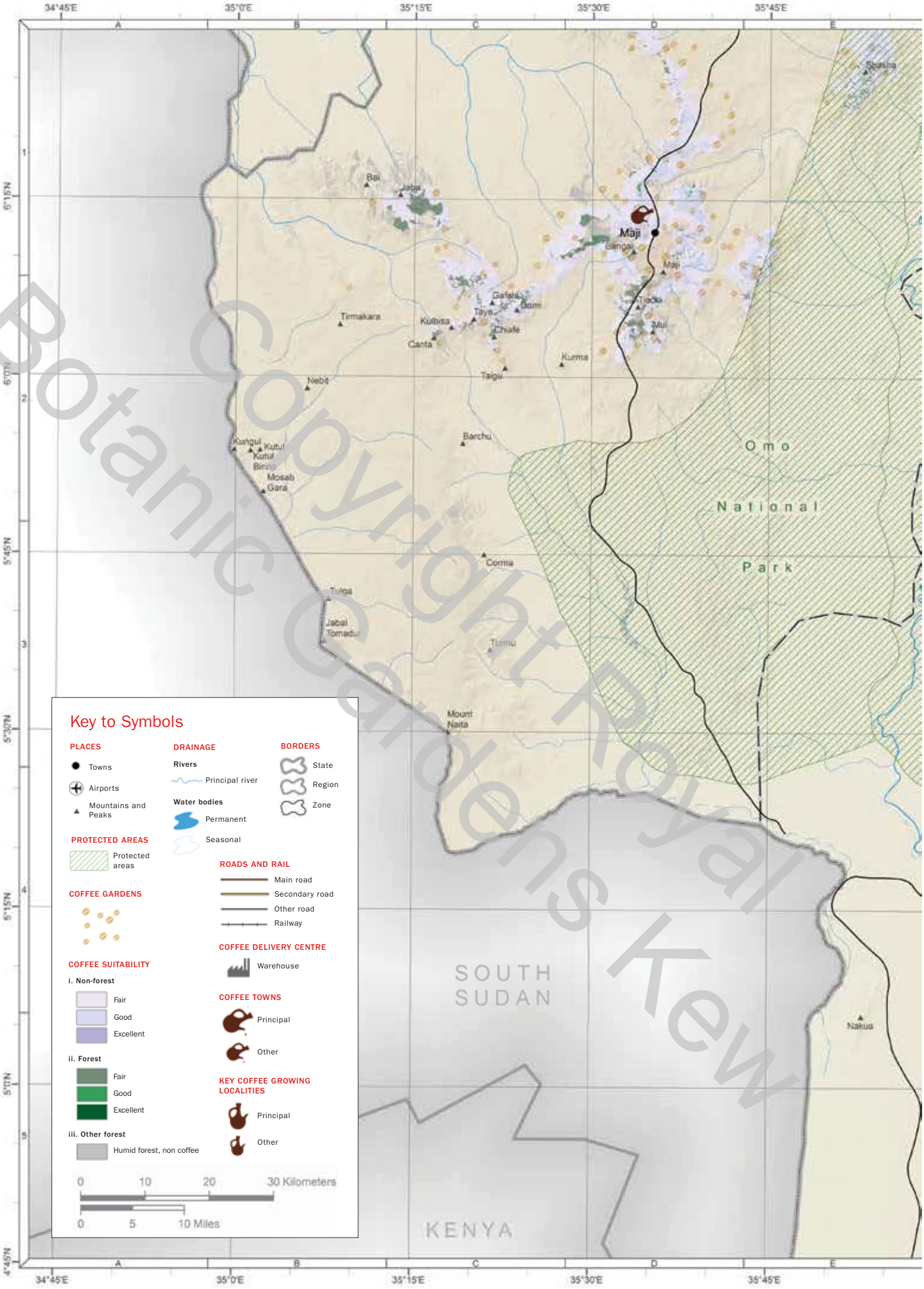
iii. Other forest
- Humid forest, non coffee

KEY COFFEE-GROWING LOCALITIES
- Principal
- Other

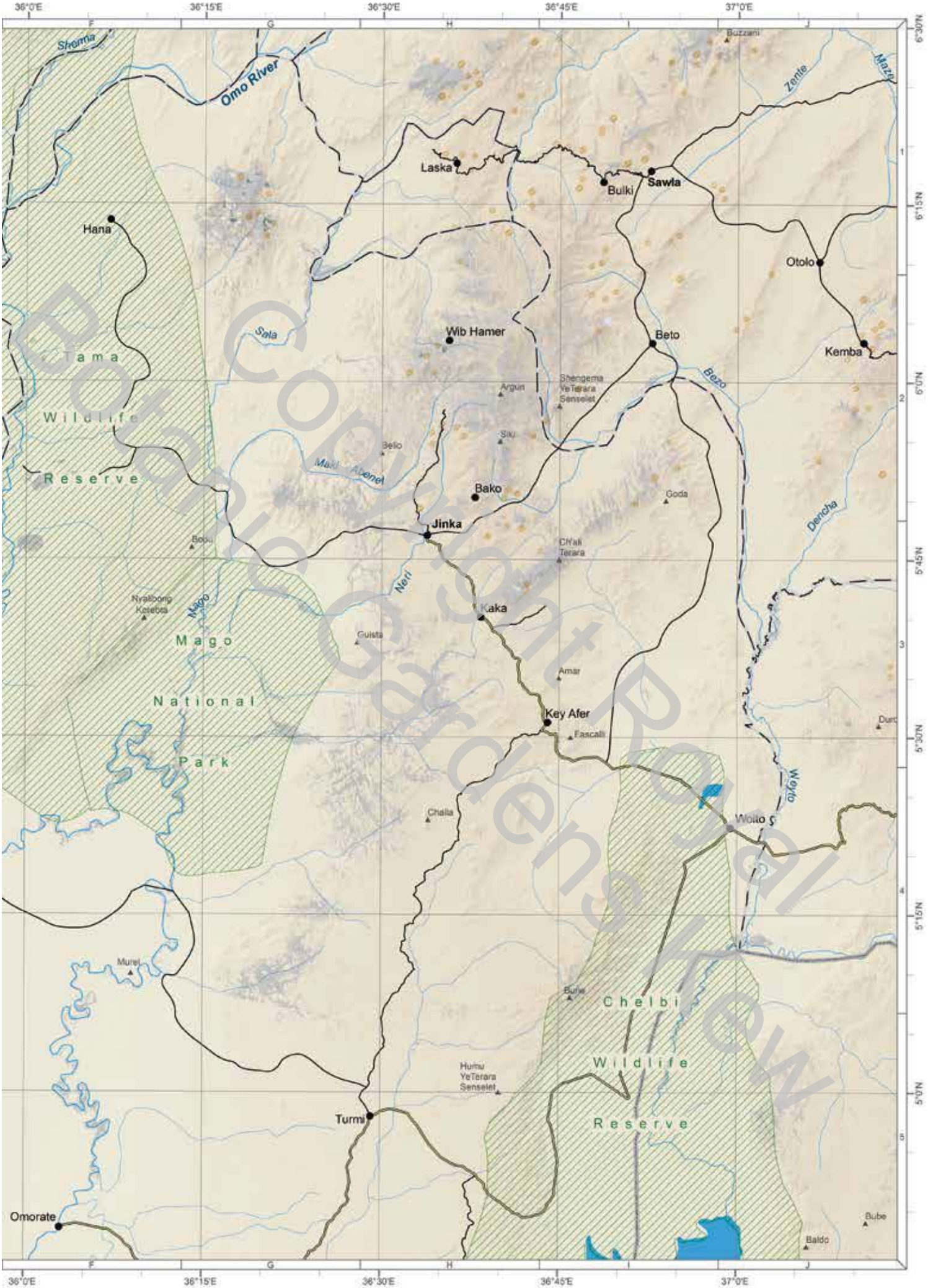
COFFEE DELIVERY CENTRE
- Warehouse

COFFEE TOWNS
- Principal
- Other

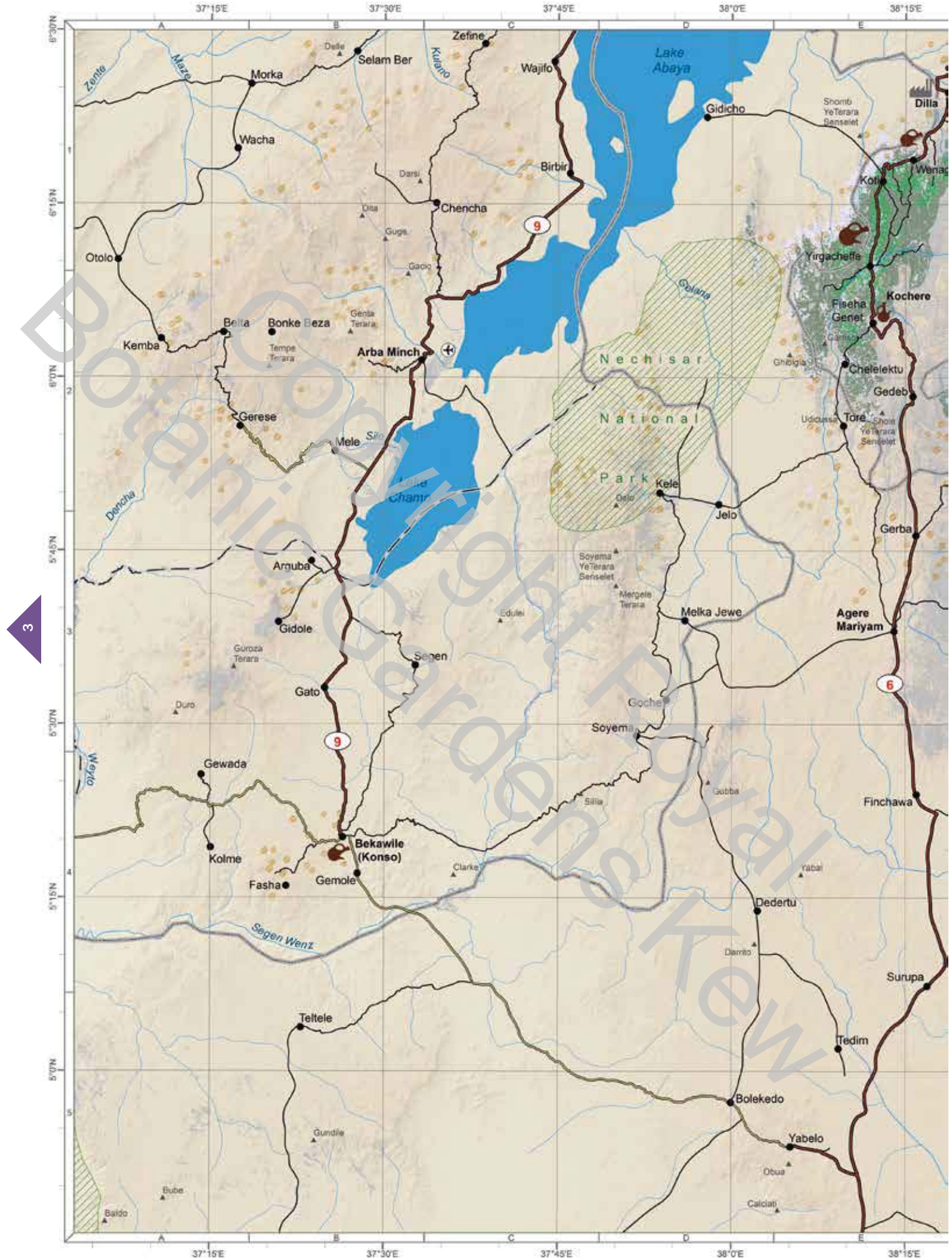
COFFEE GARDENS



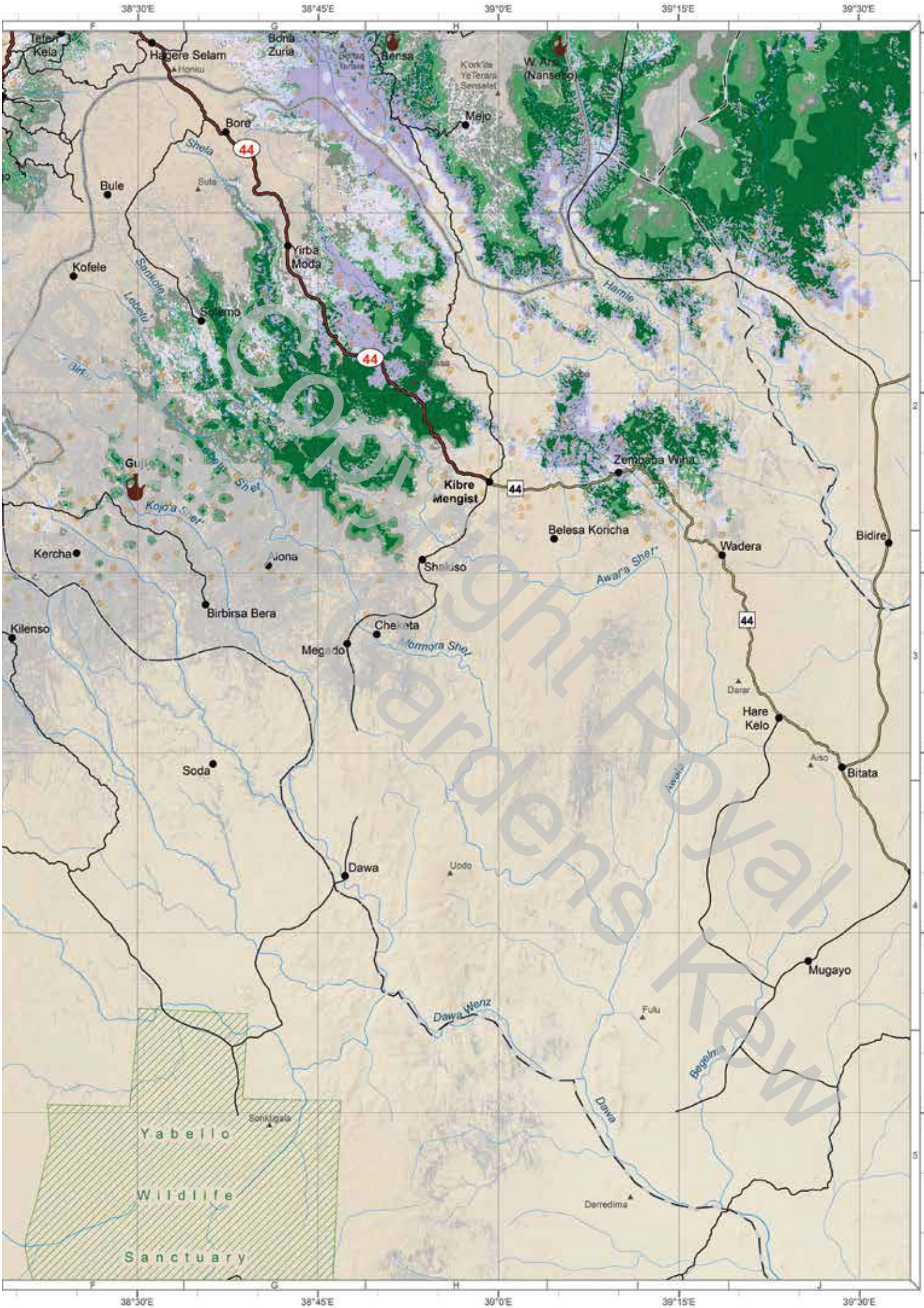
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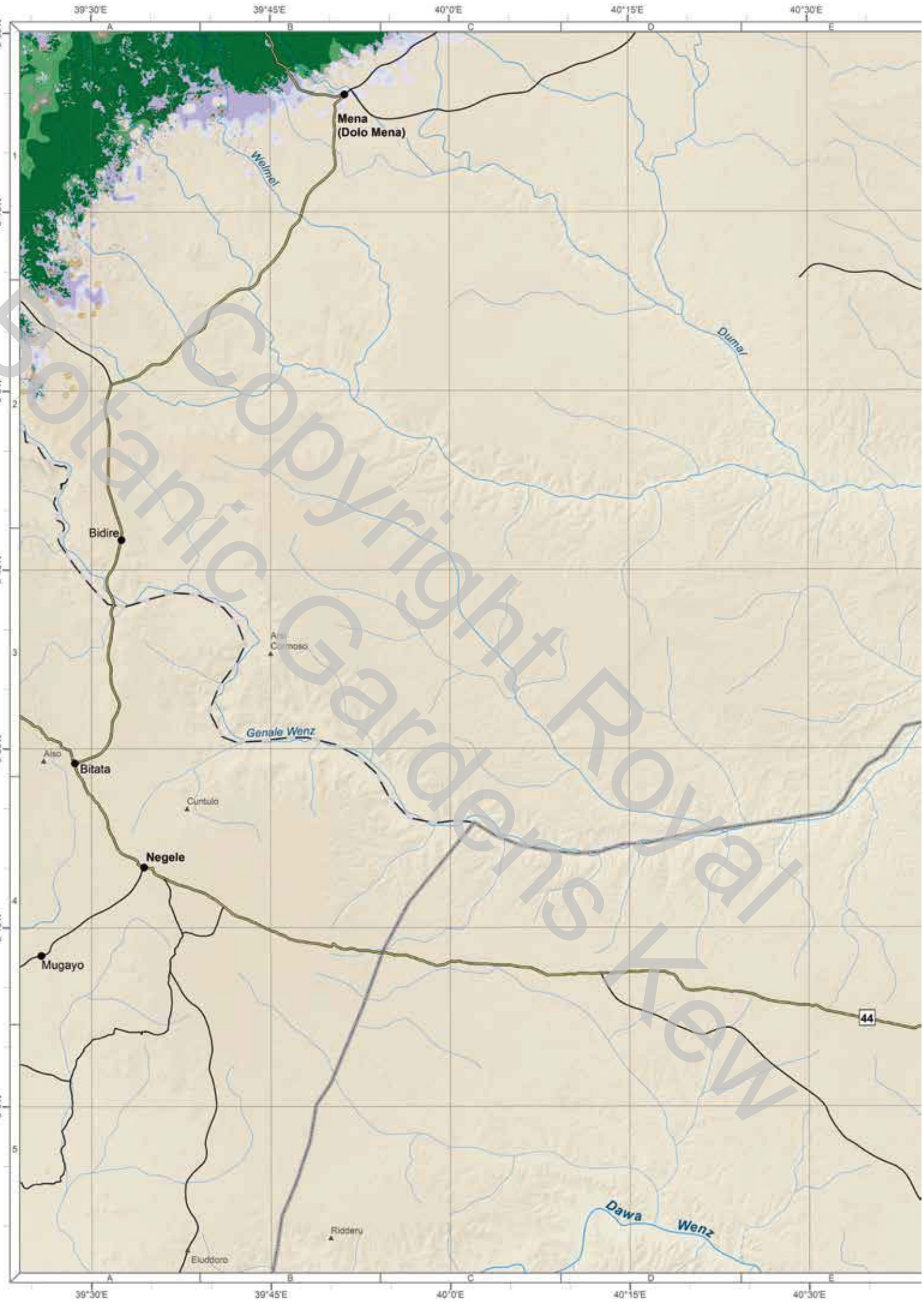
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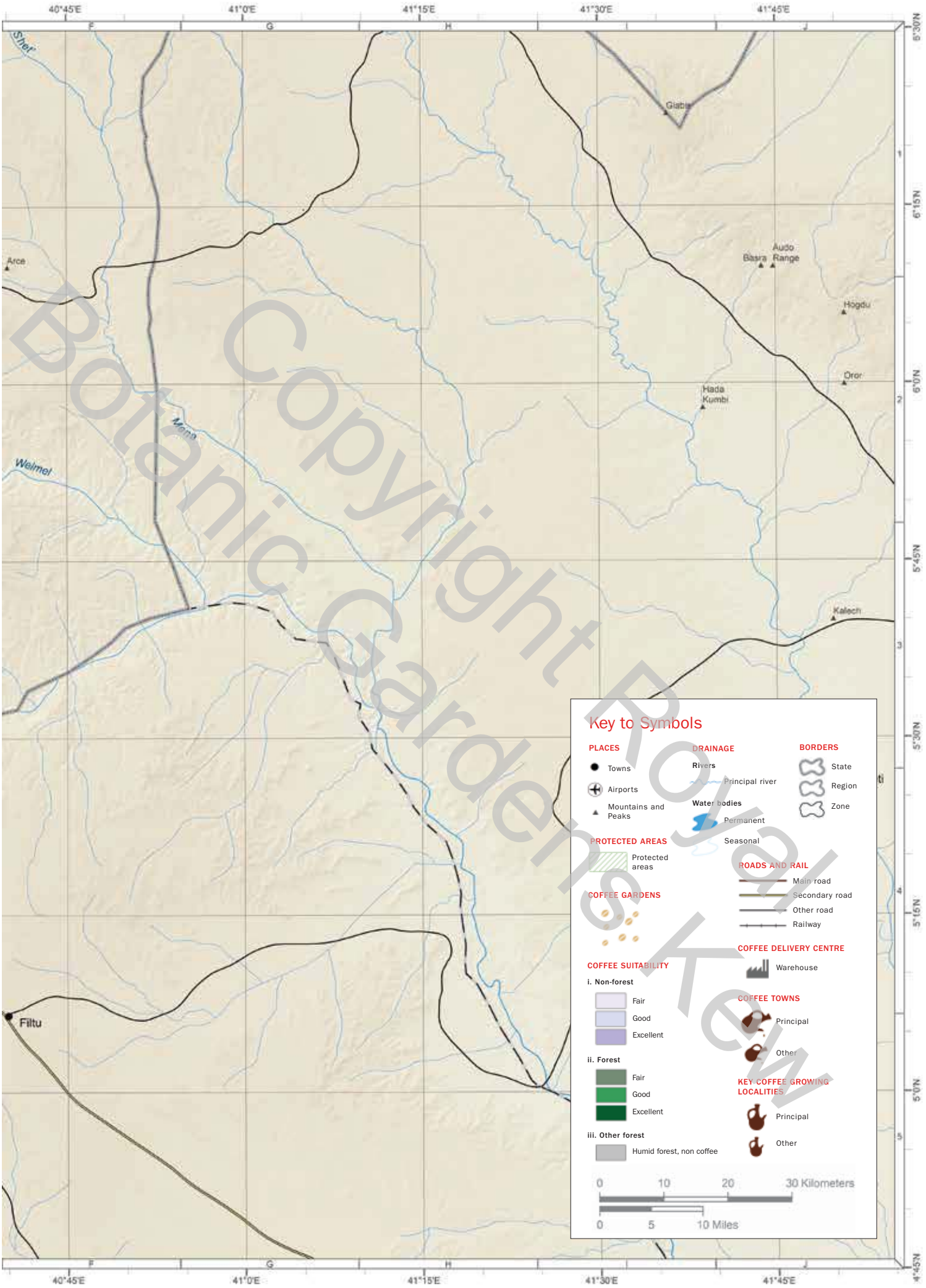
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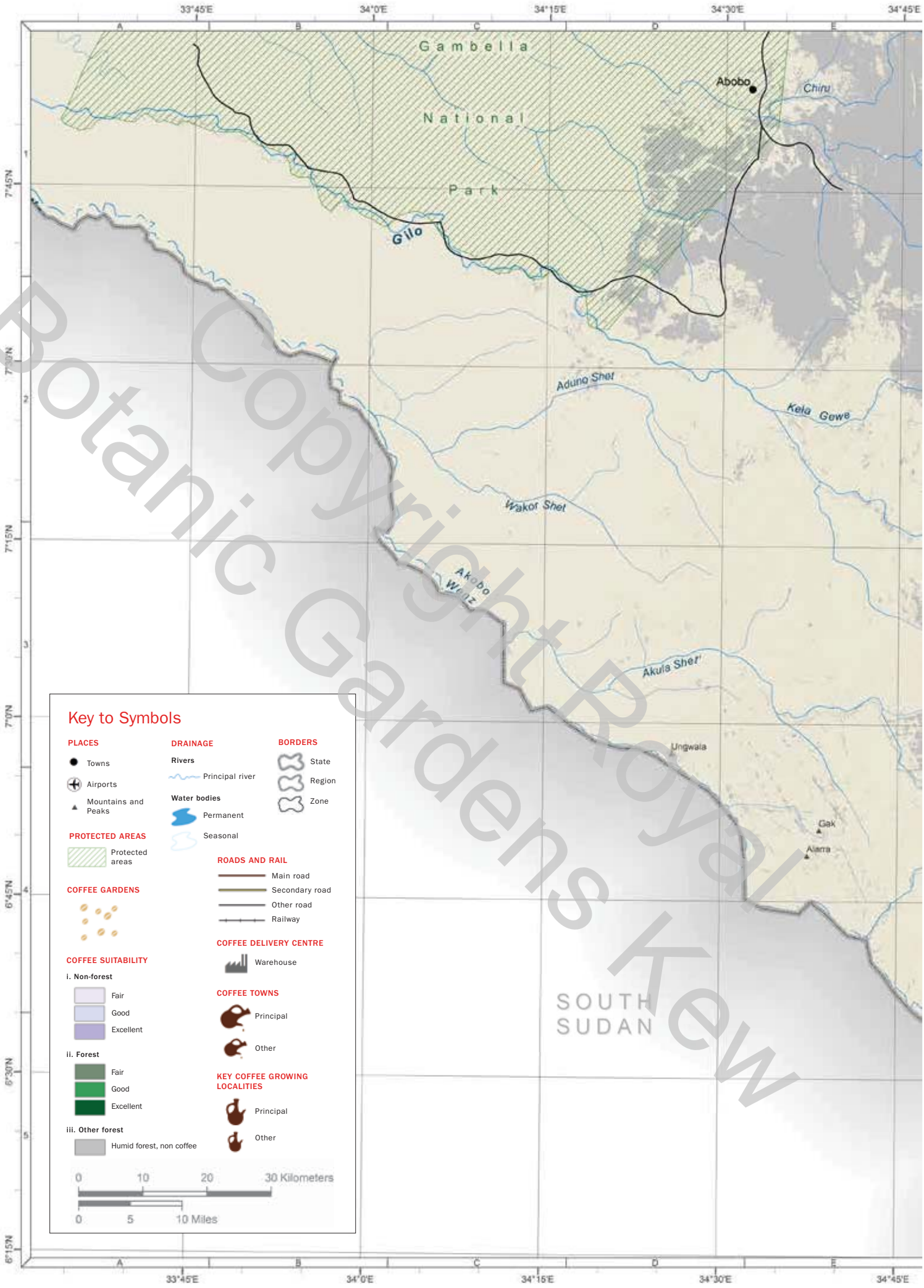
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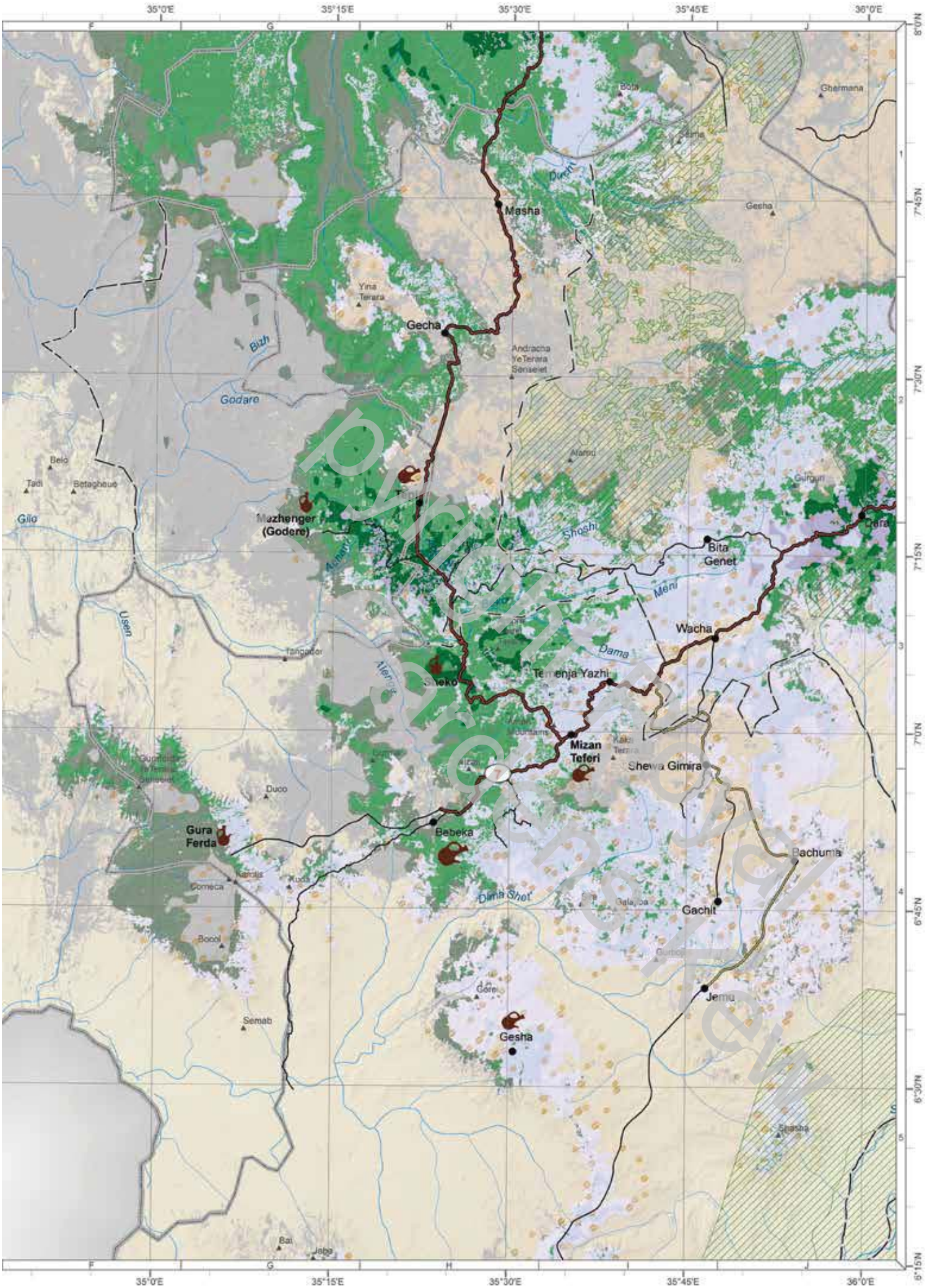
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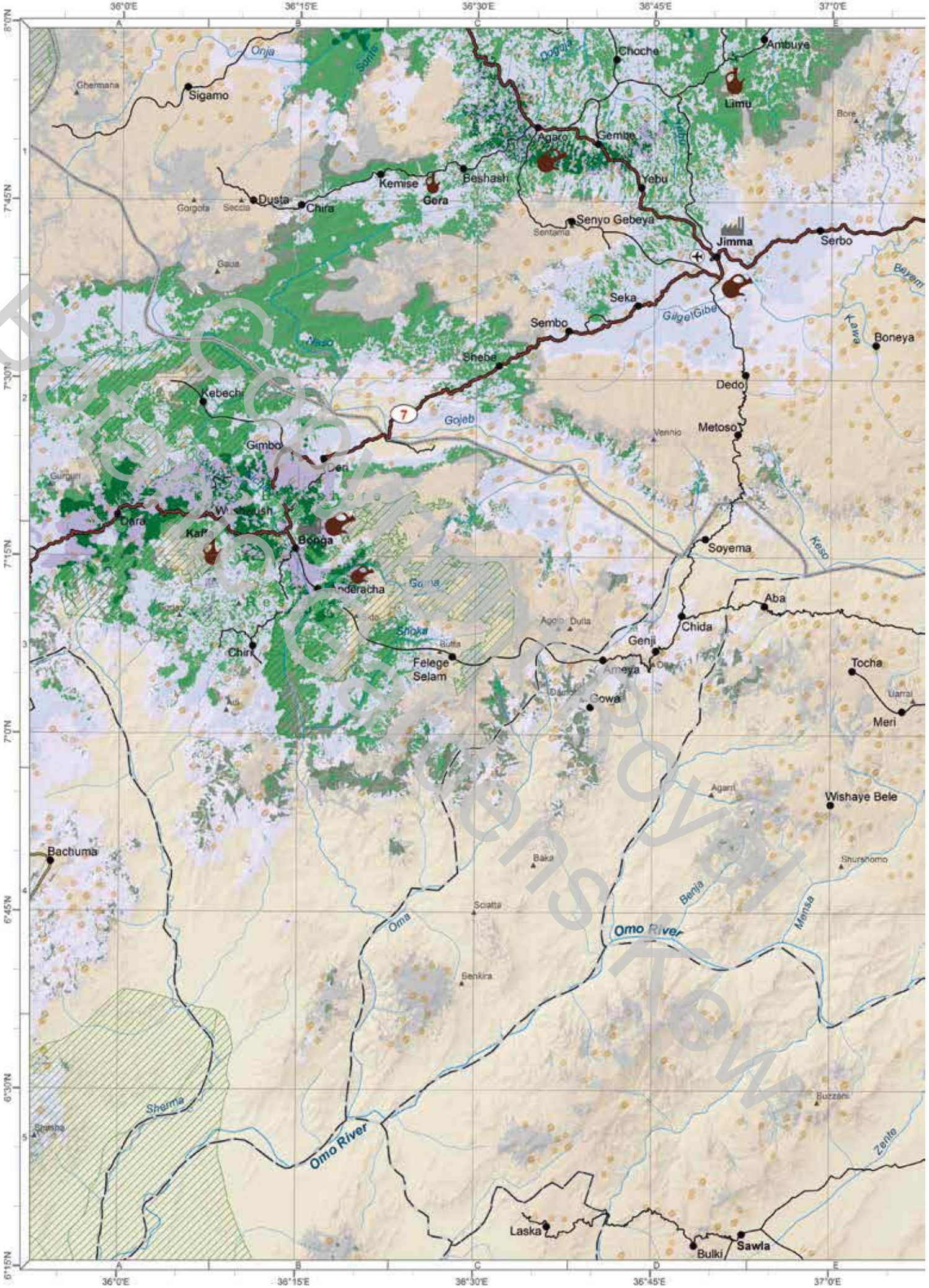


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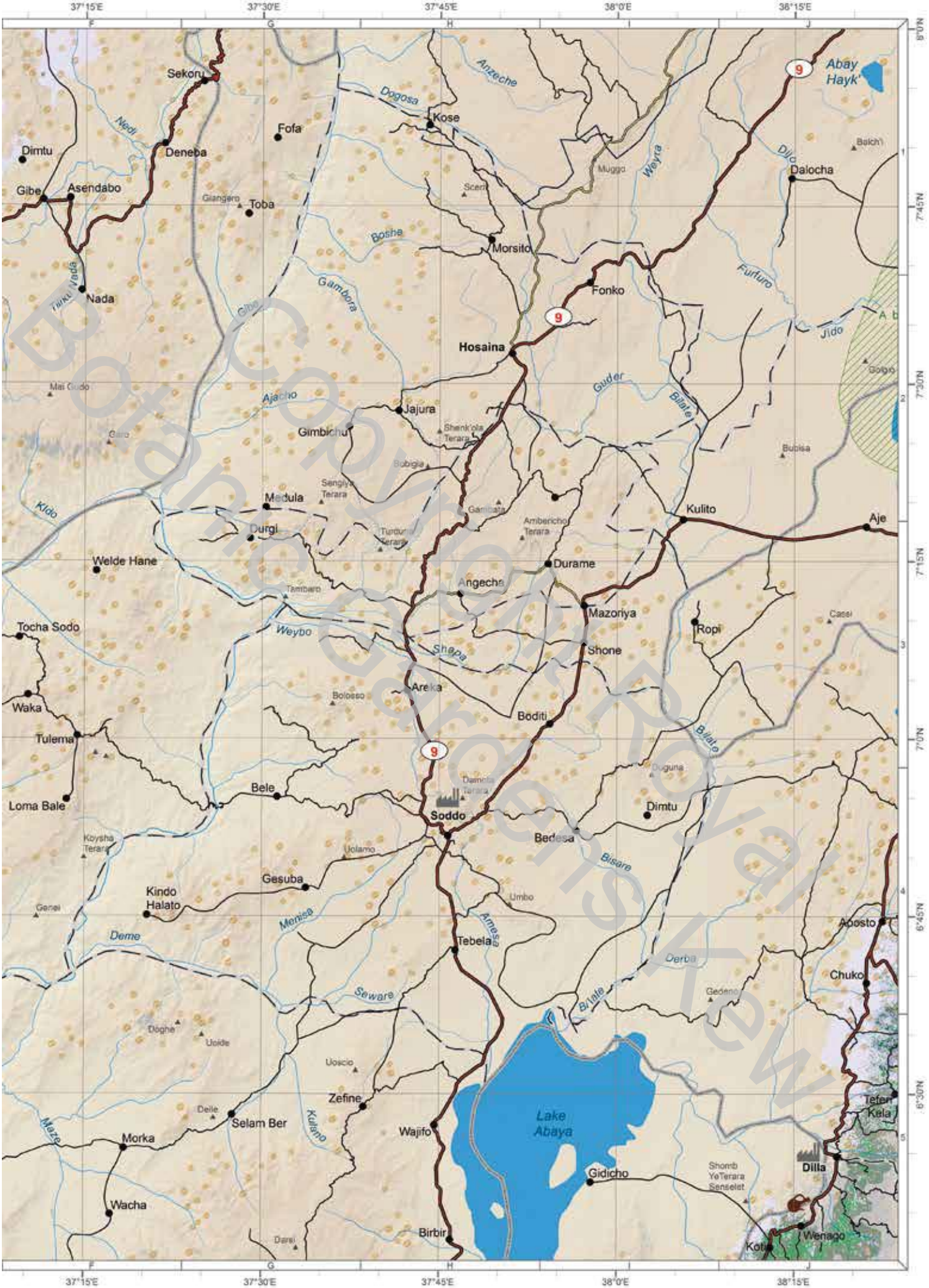


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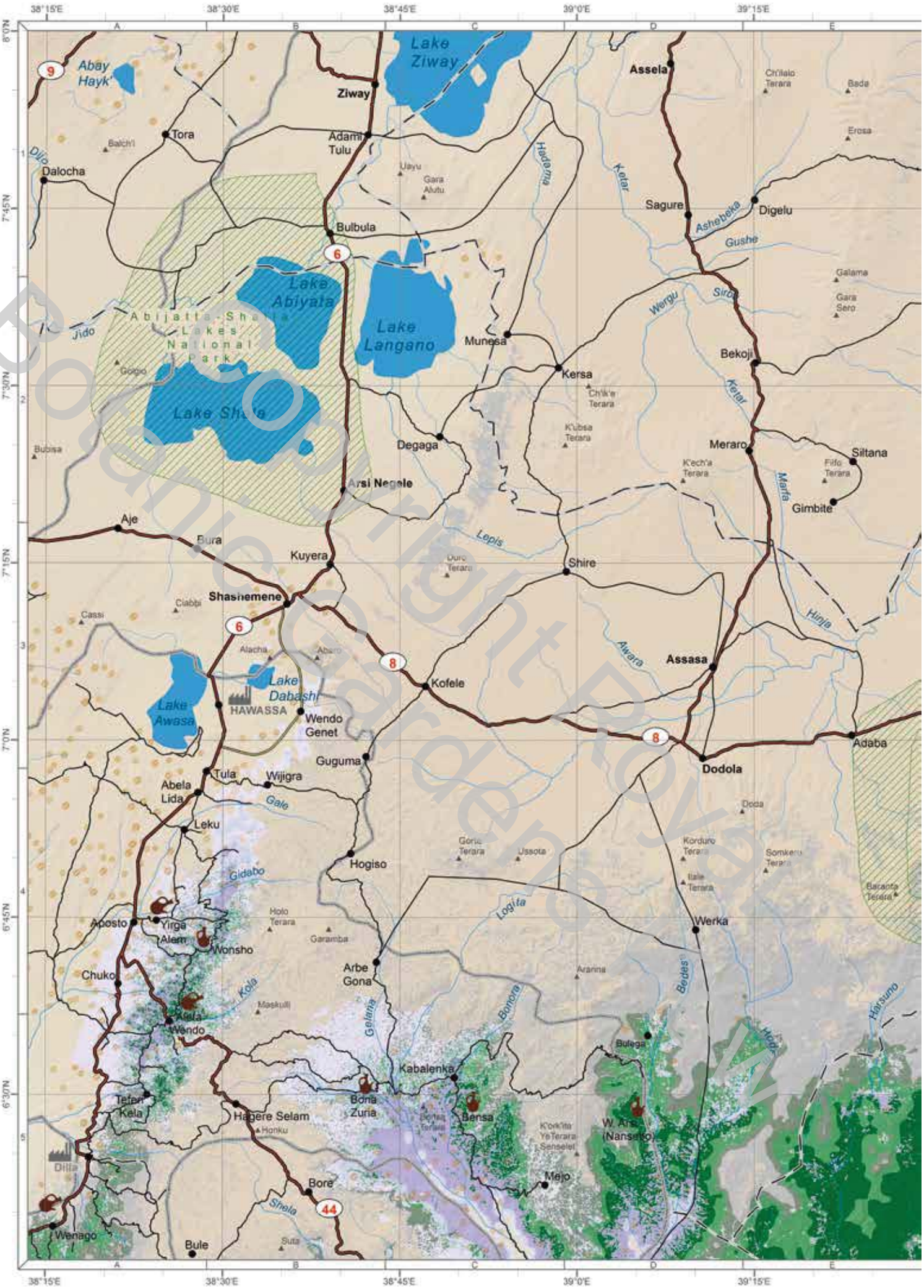

35°0'E
35°15'E
35°30'E
35°45'E
36°0'E
8°0'N
7°45'N
7°30'N
7°15'N
7°0'N
6°45'N
6°30'N
6°15'N
Masha
Gecha
Yina Terara
Andracha YeTerara Sensebet
Bizh
Godare
Belo
Tadi
Betagheue
Gilo
Mazhenger (Godere)
Usen
Tangador
Alamu
Shoshi
Bita Genet
Wacha
Dama
Mizan Teferi
Shewa Gimira
Duco
Gura Ferda
Bebeka
Dima Shot'
Bachuma
Gachit
Jemu
Gesha
Semab
Bacol
Bai
Jaba
Ghermana
Gesha
Gurgum
Cera
Meni
Seasha



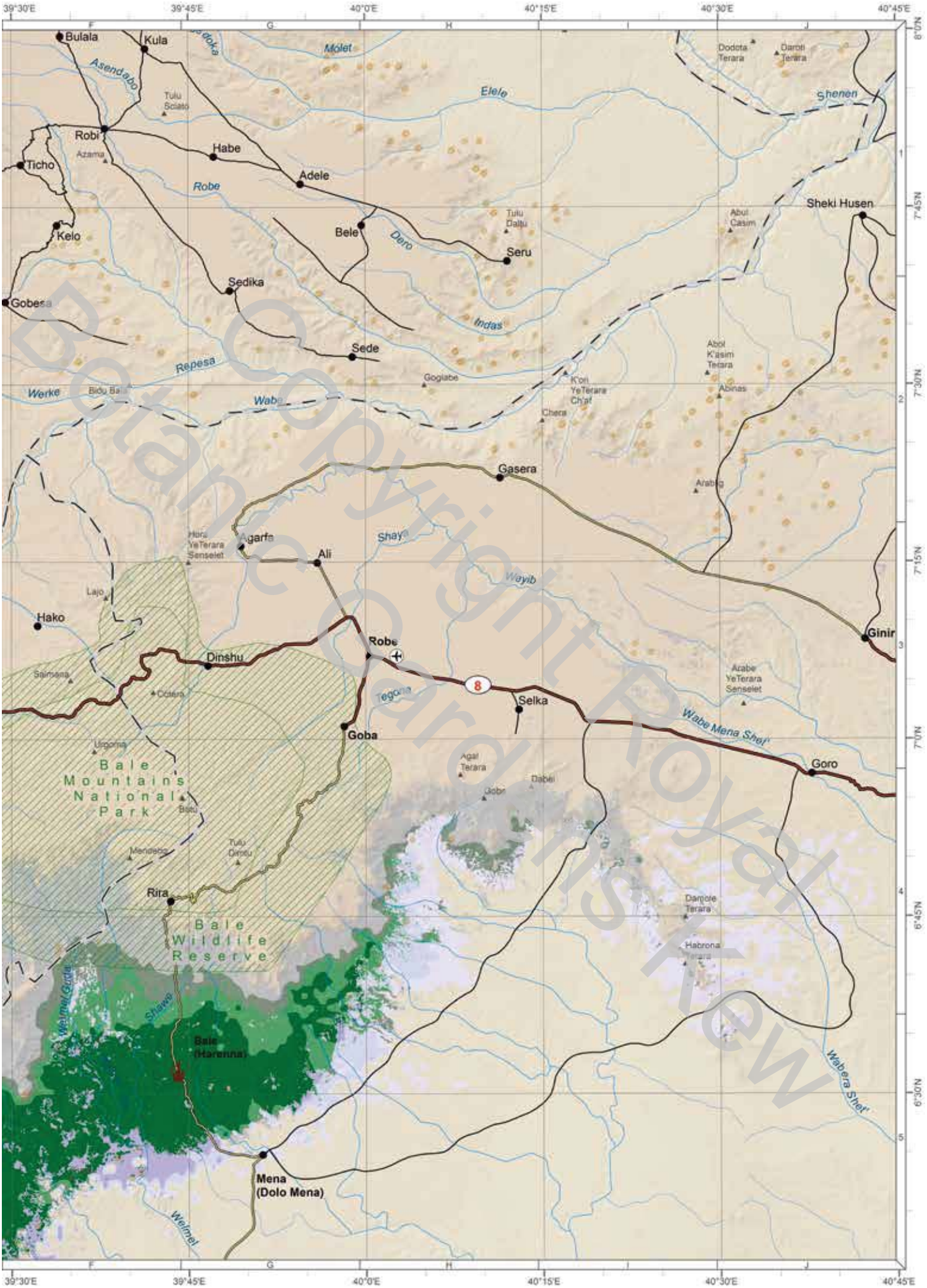
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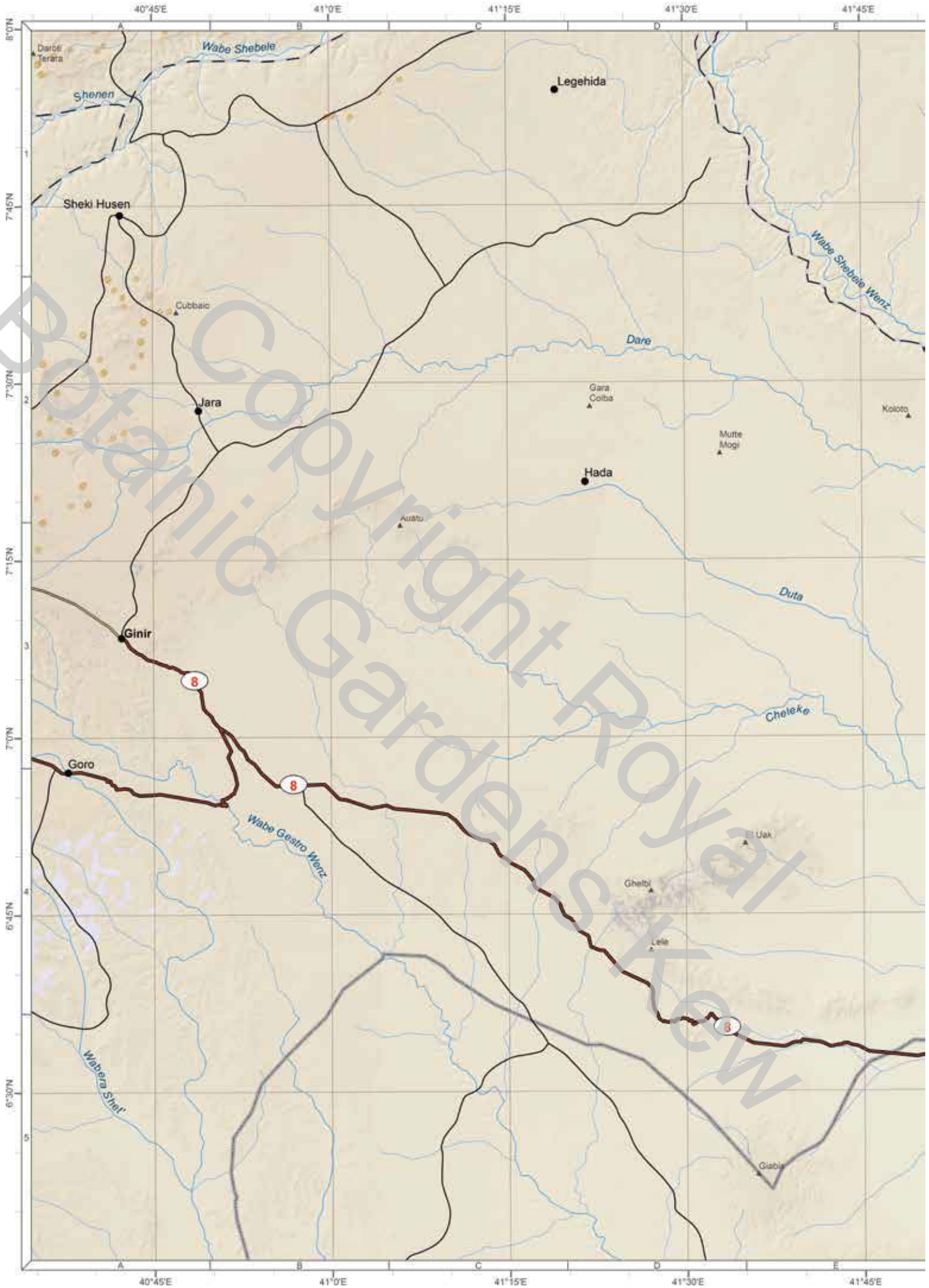
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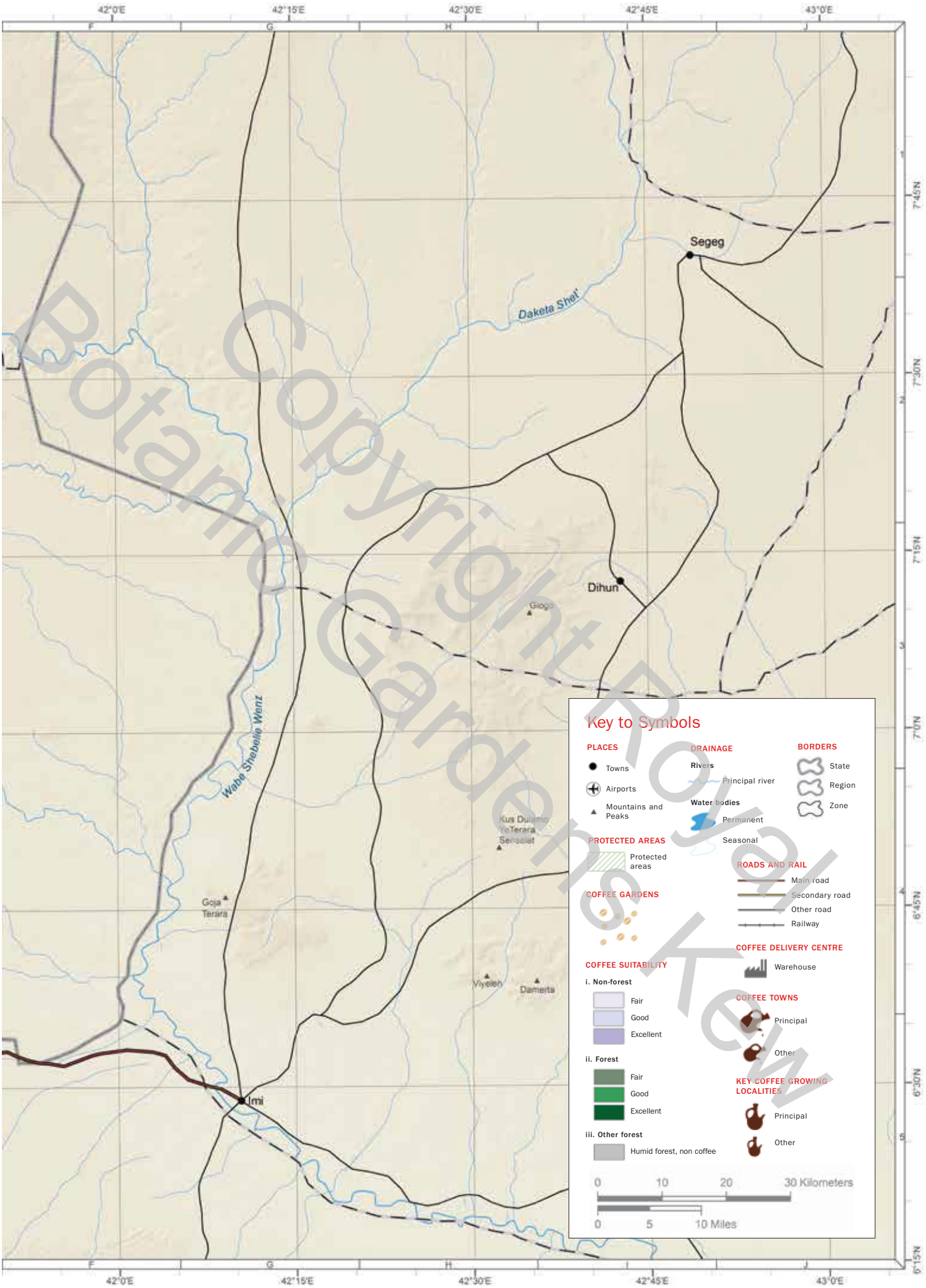
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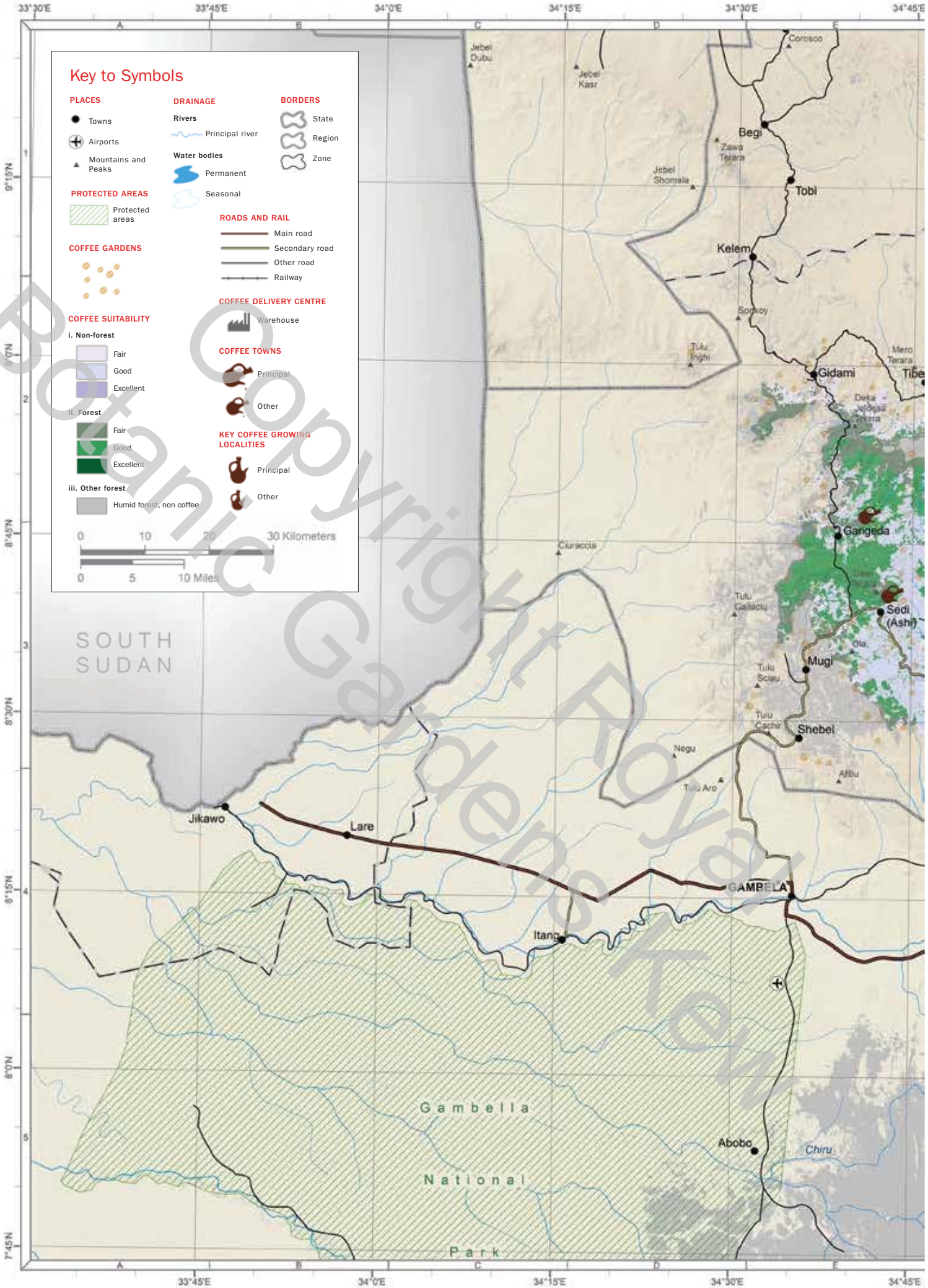
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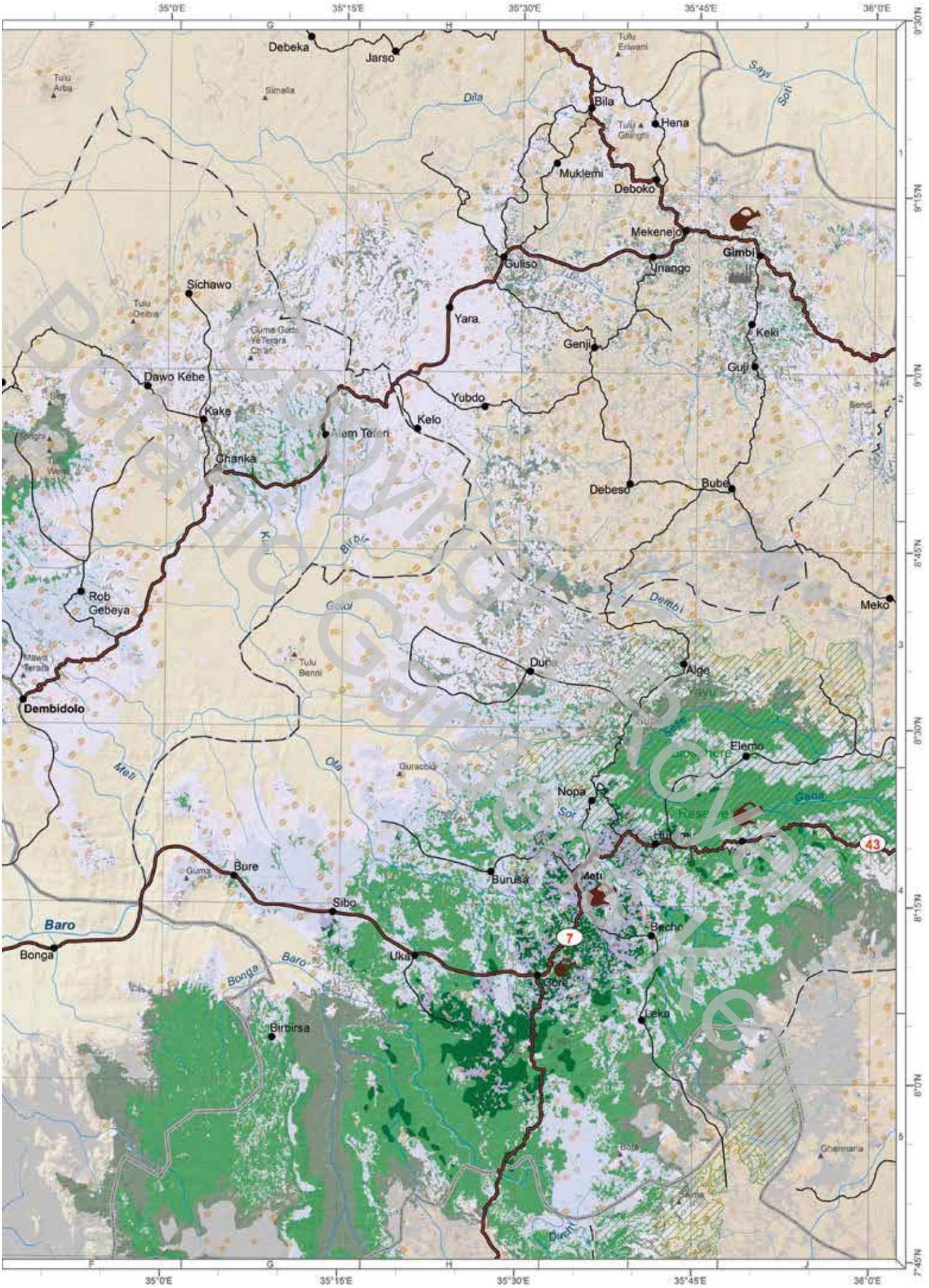
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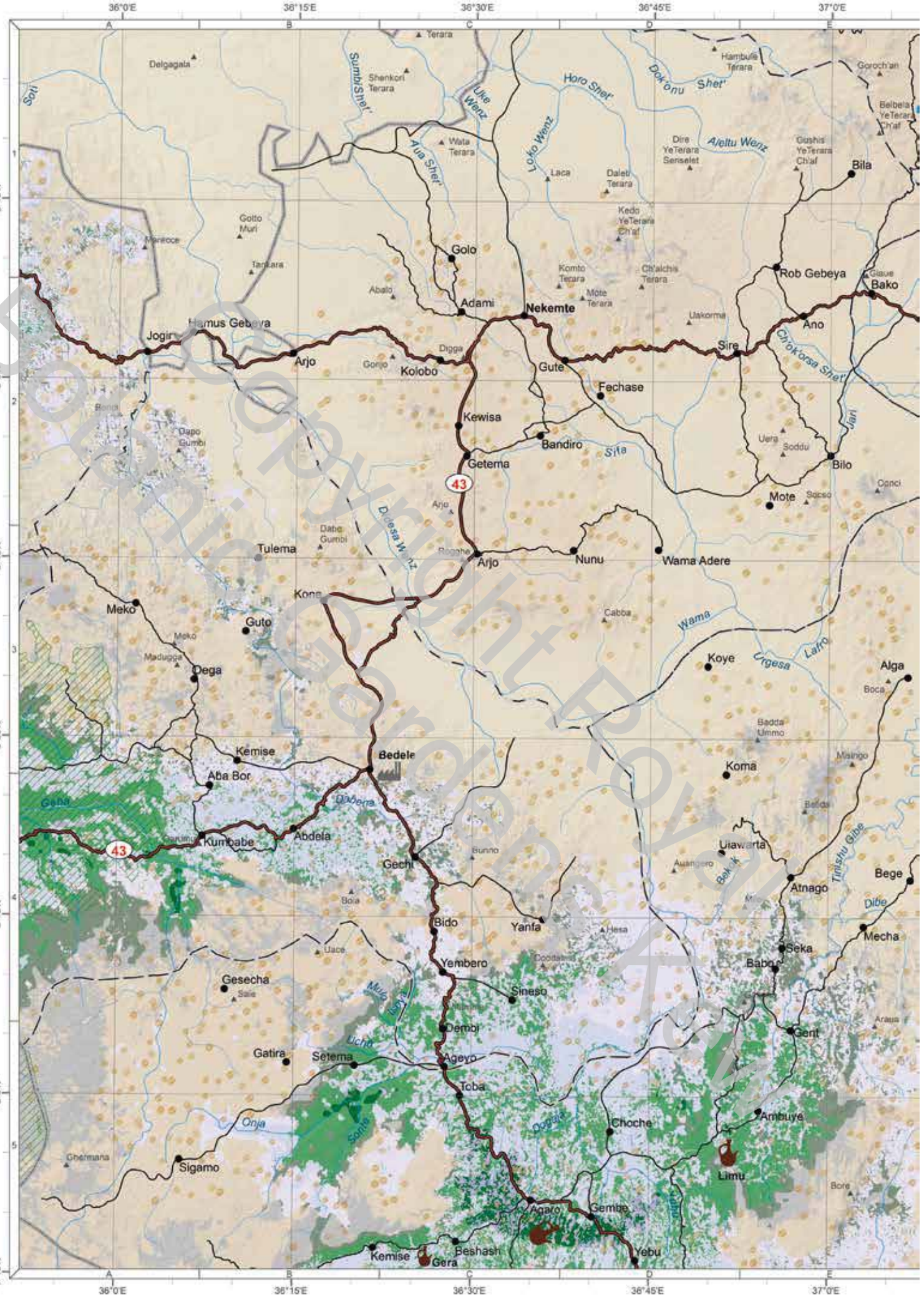
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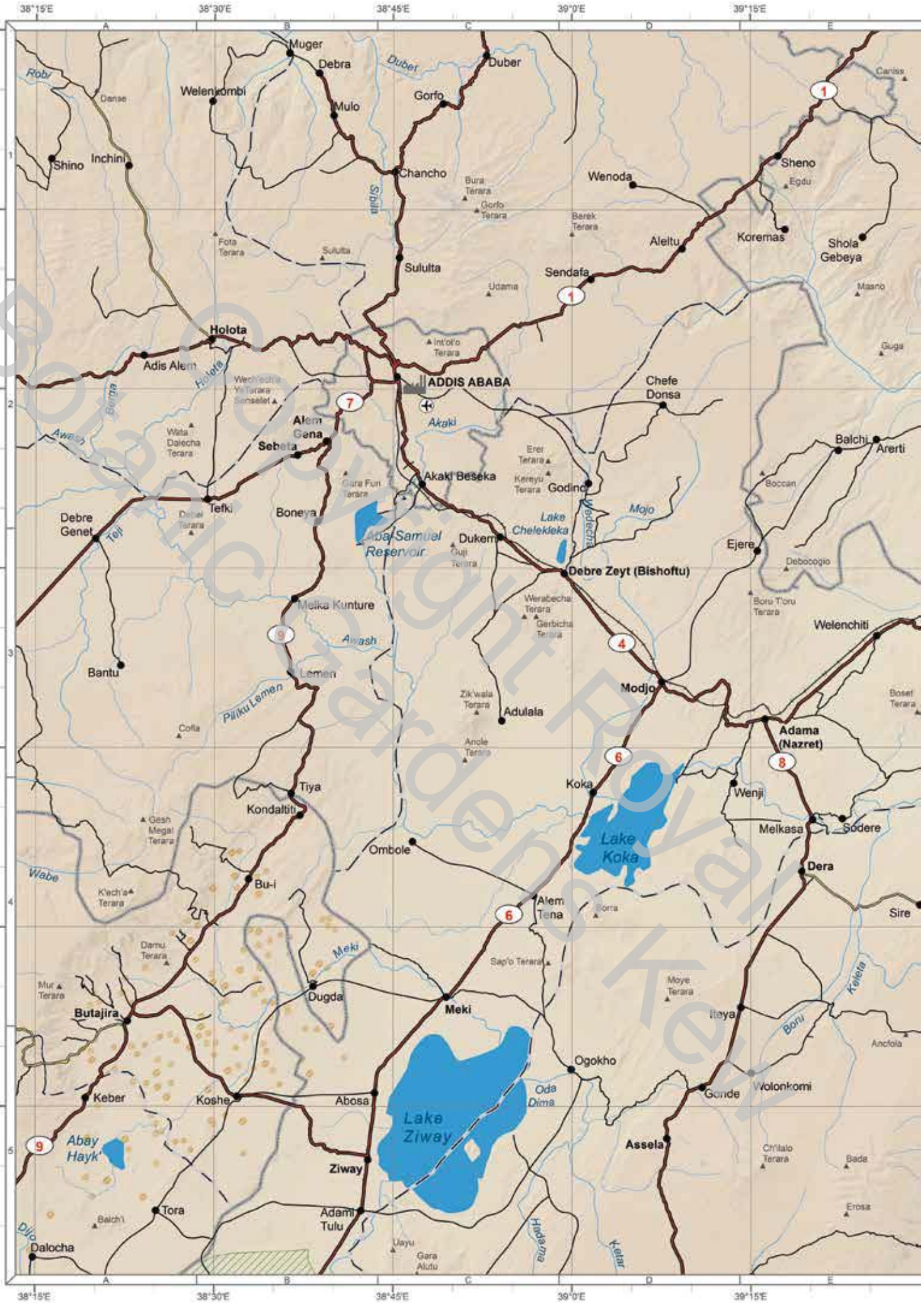
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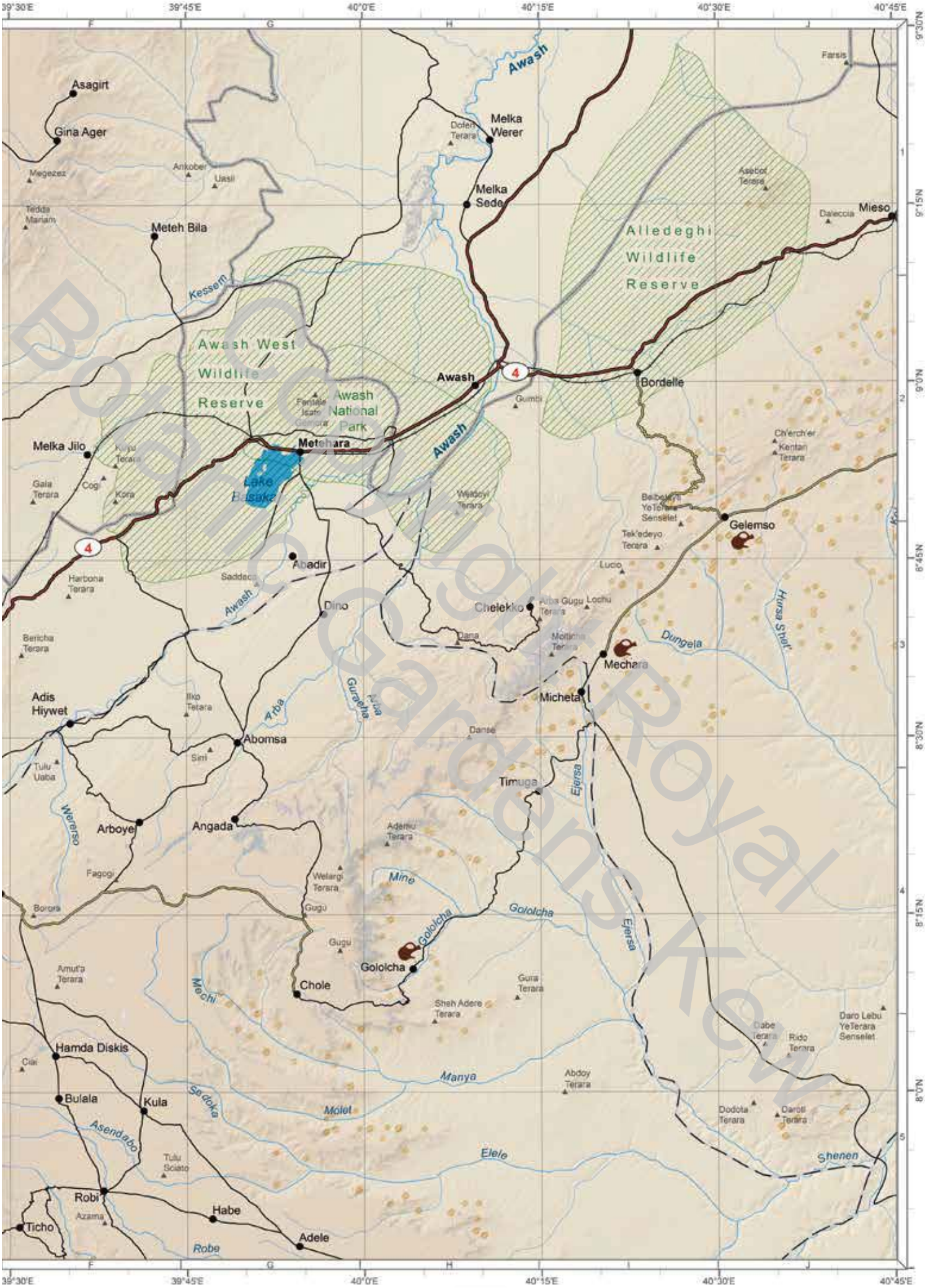
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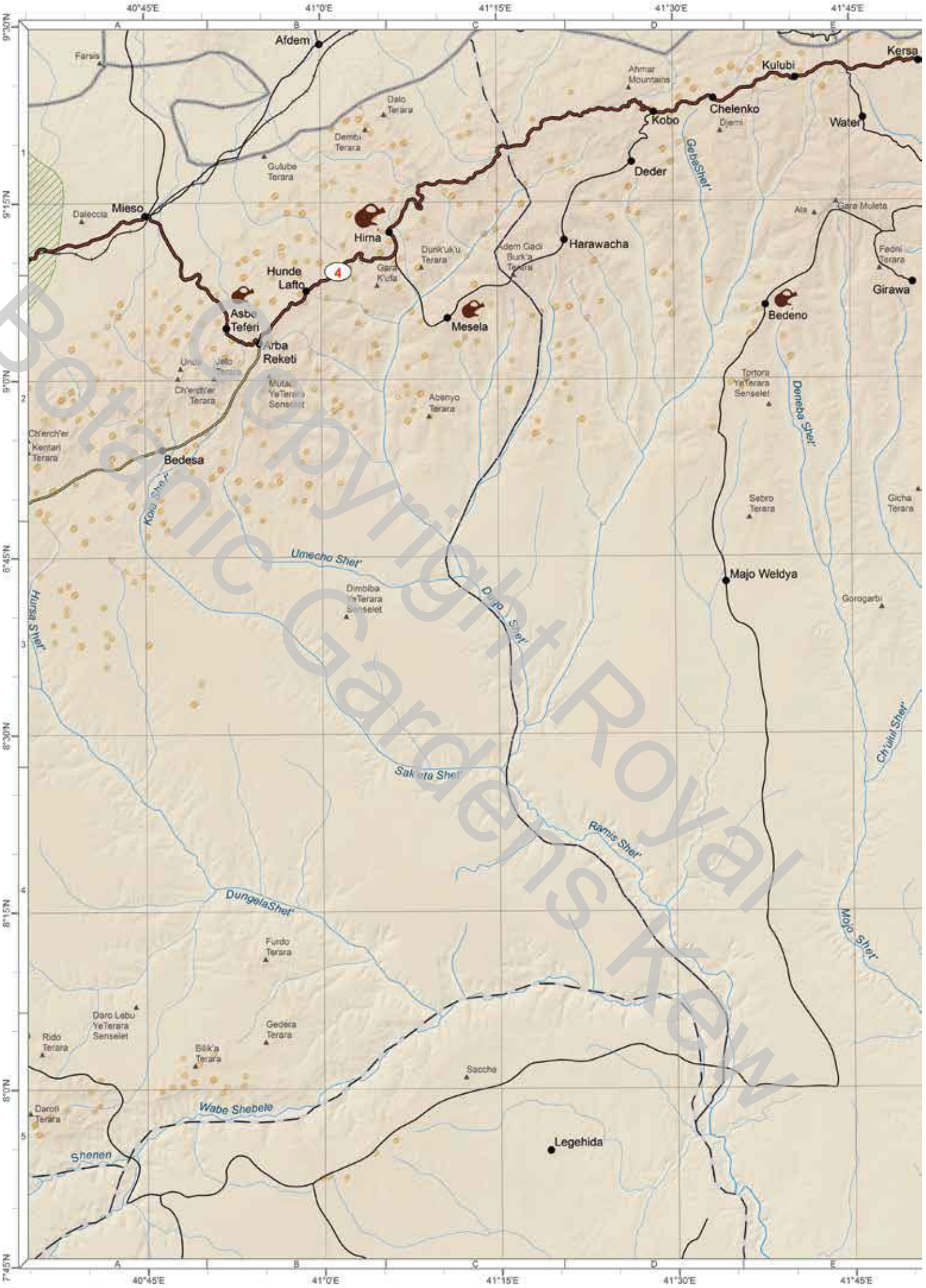
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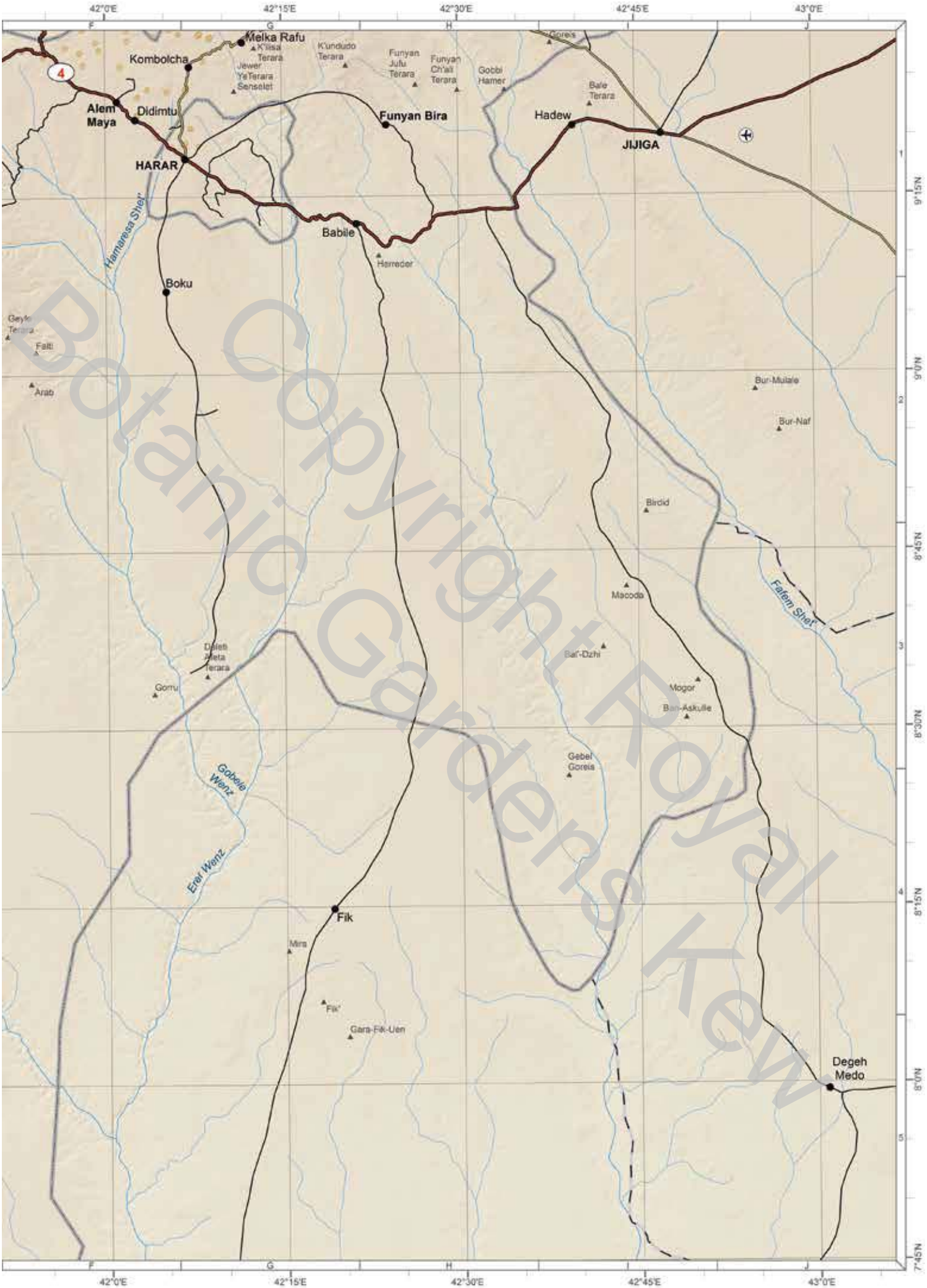
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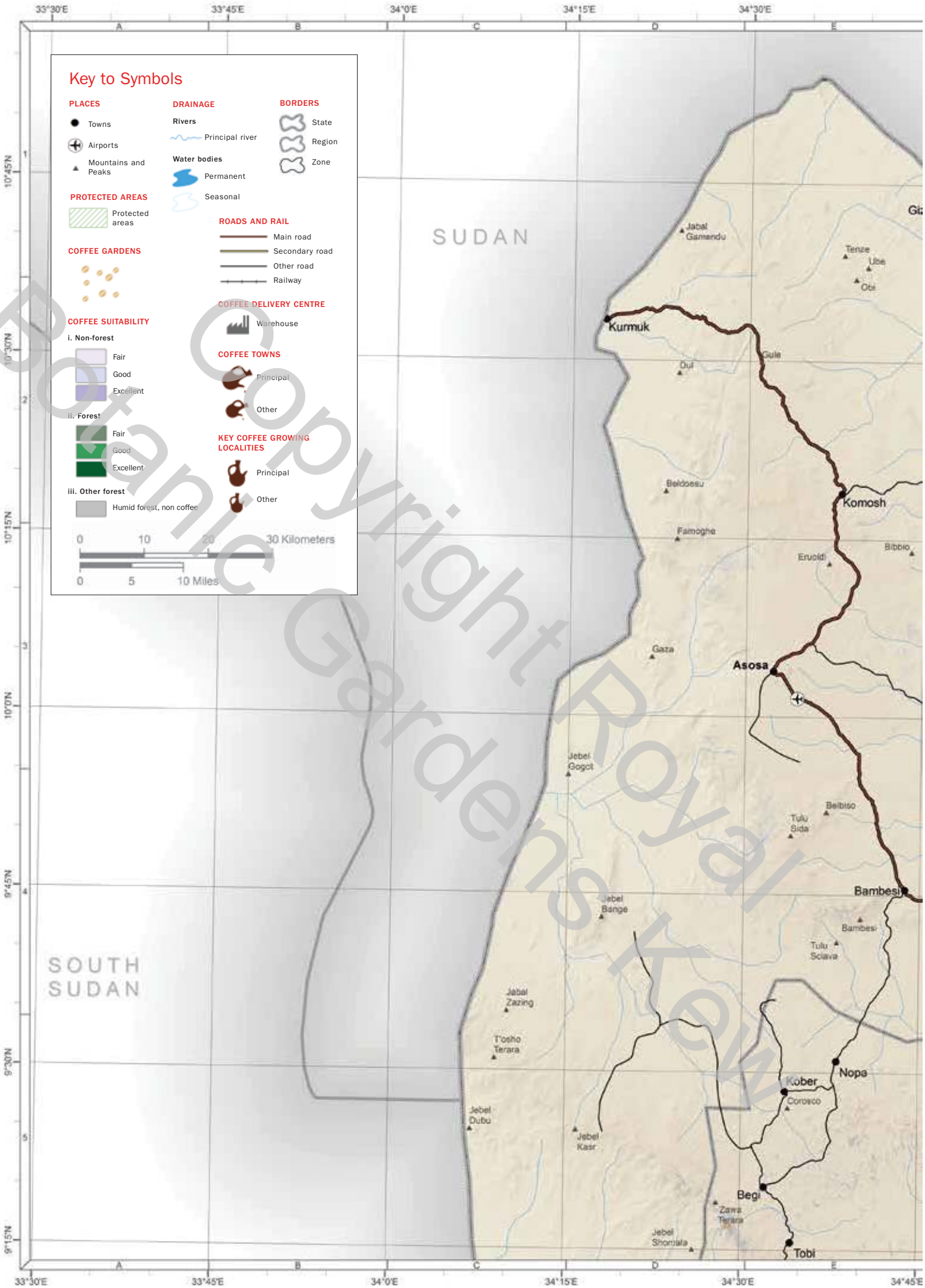
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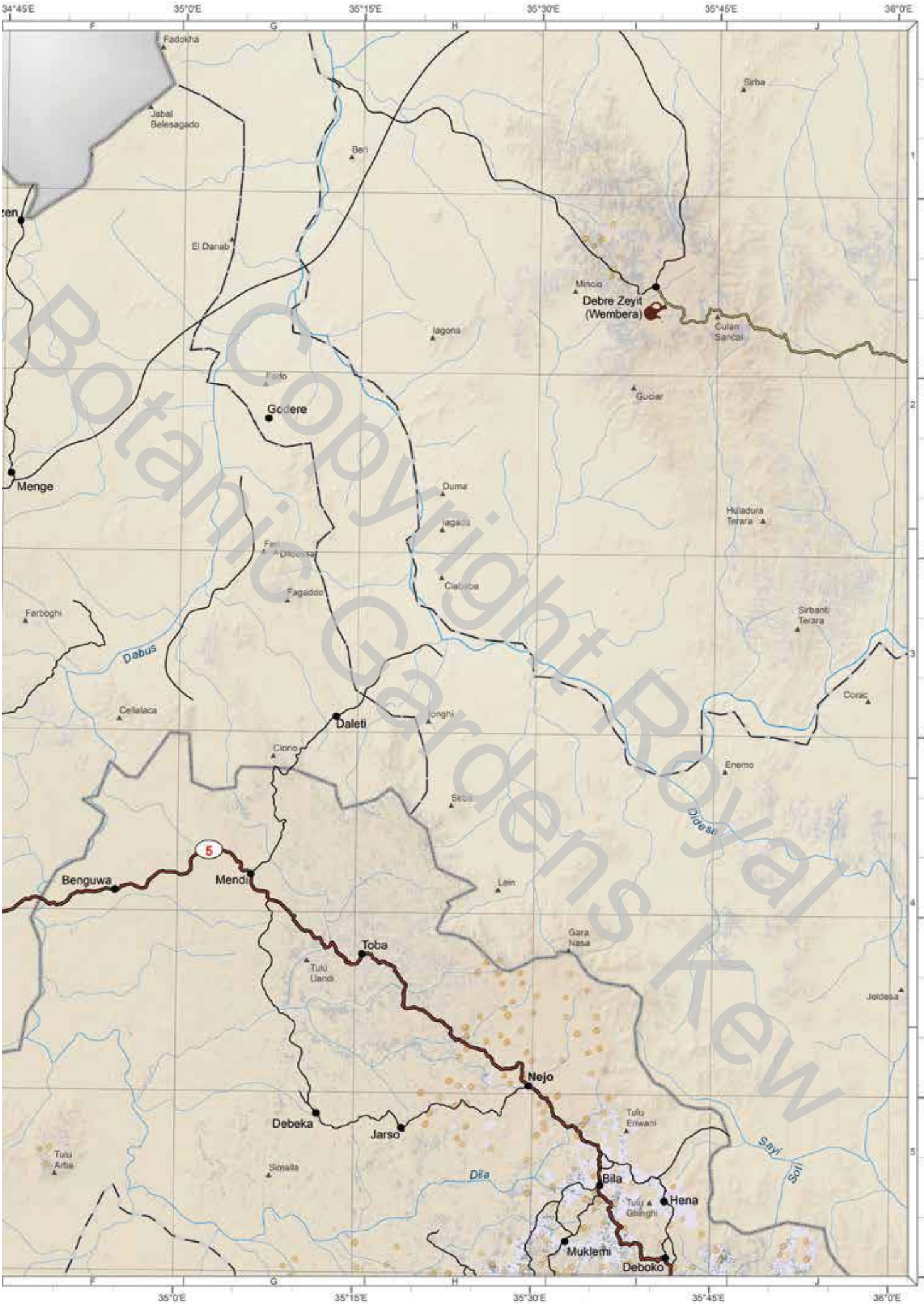
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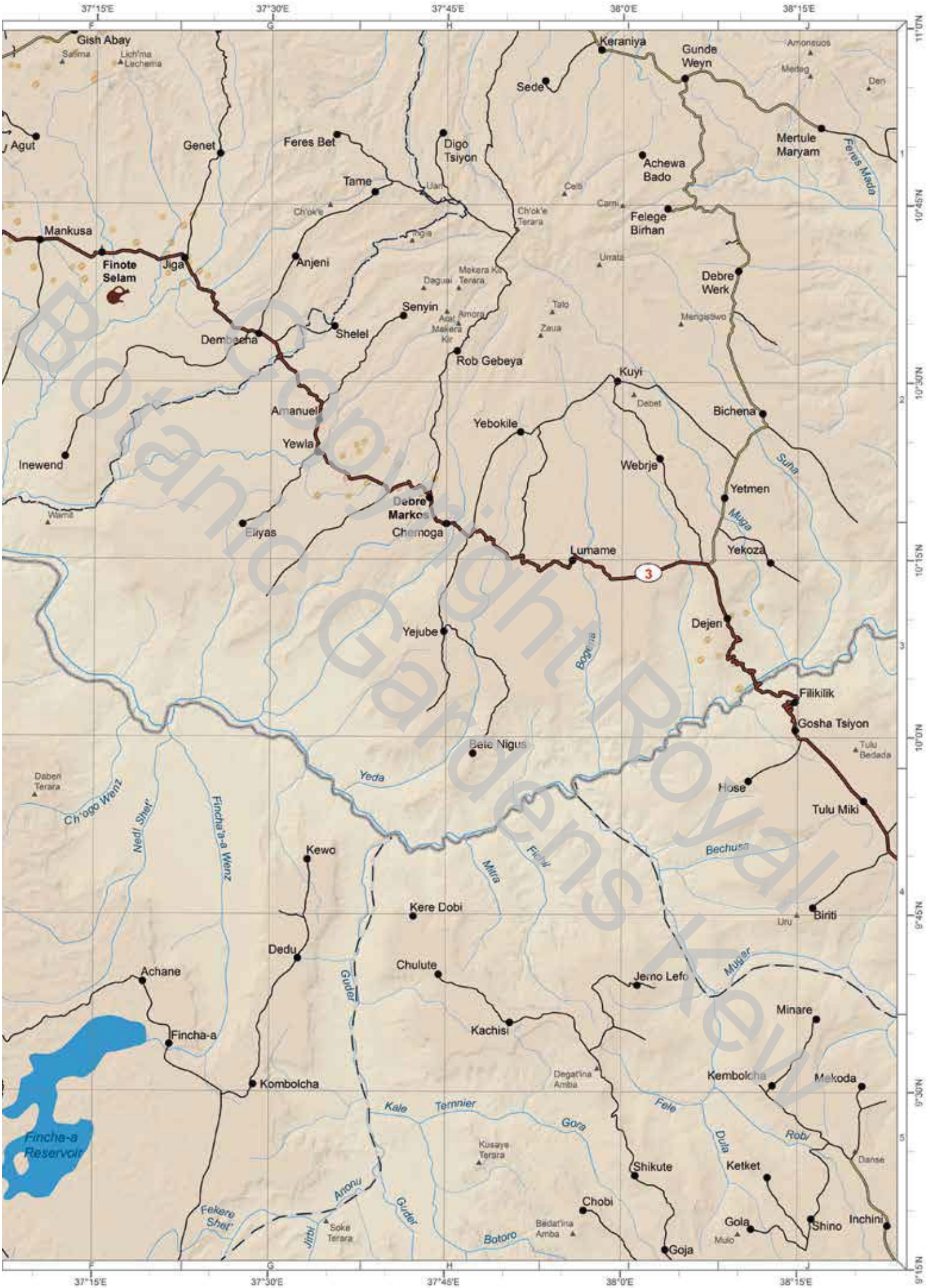
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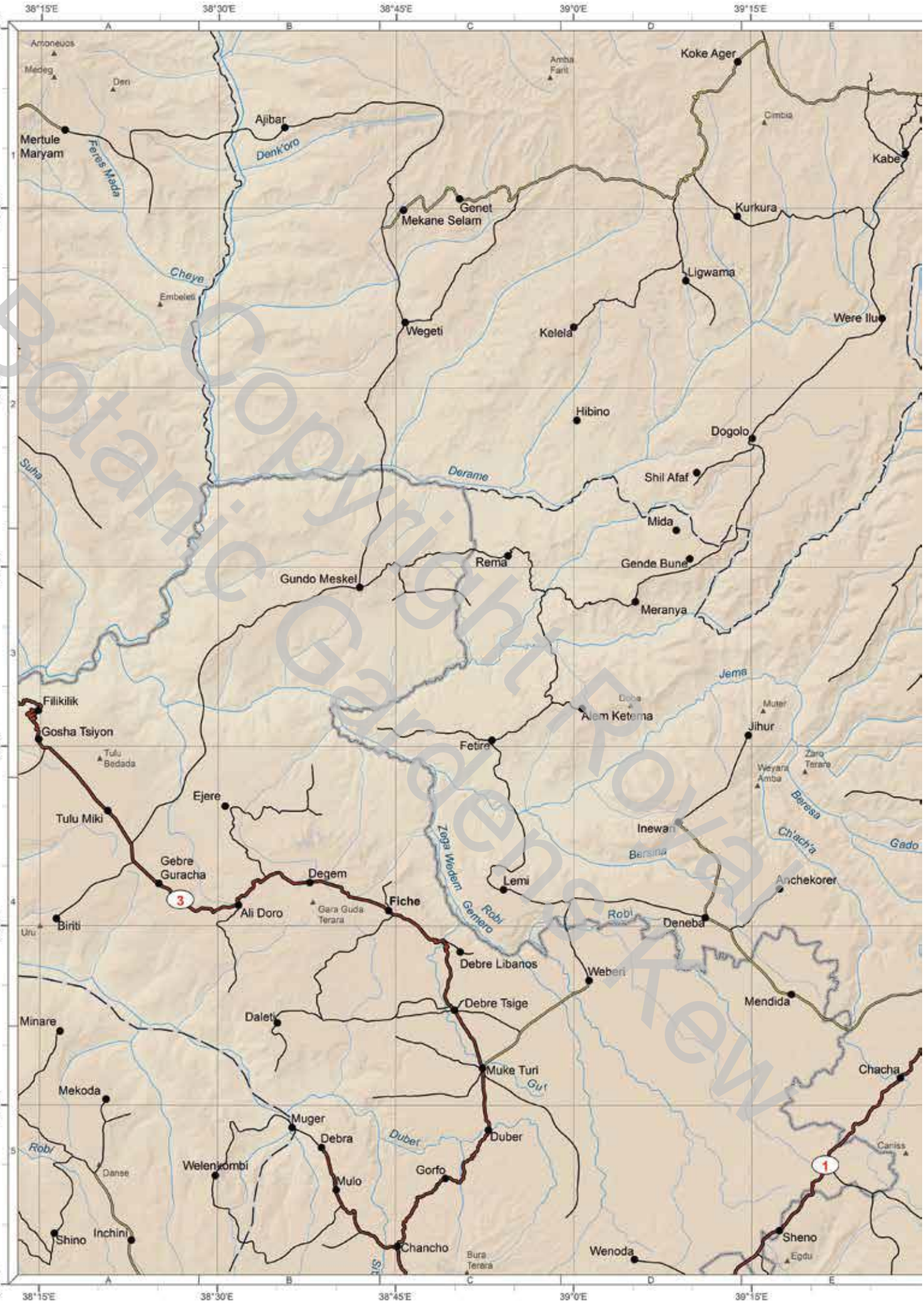
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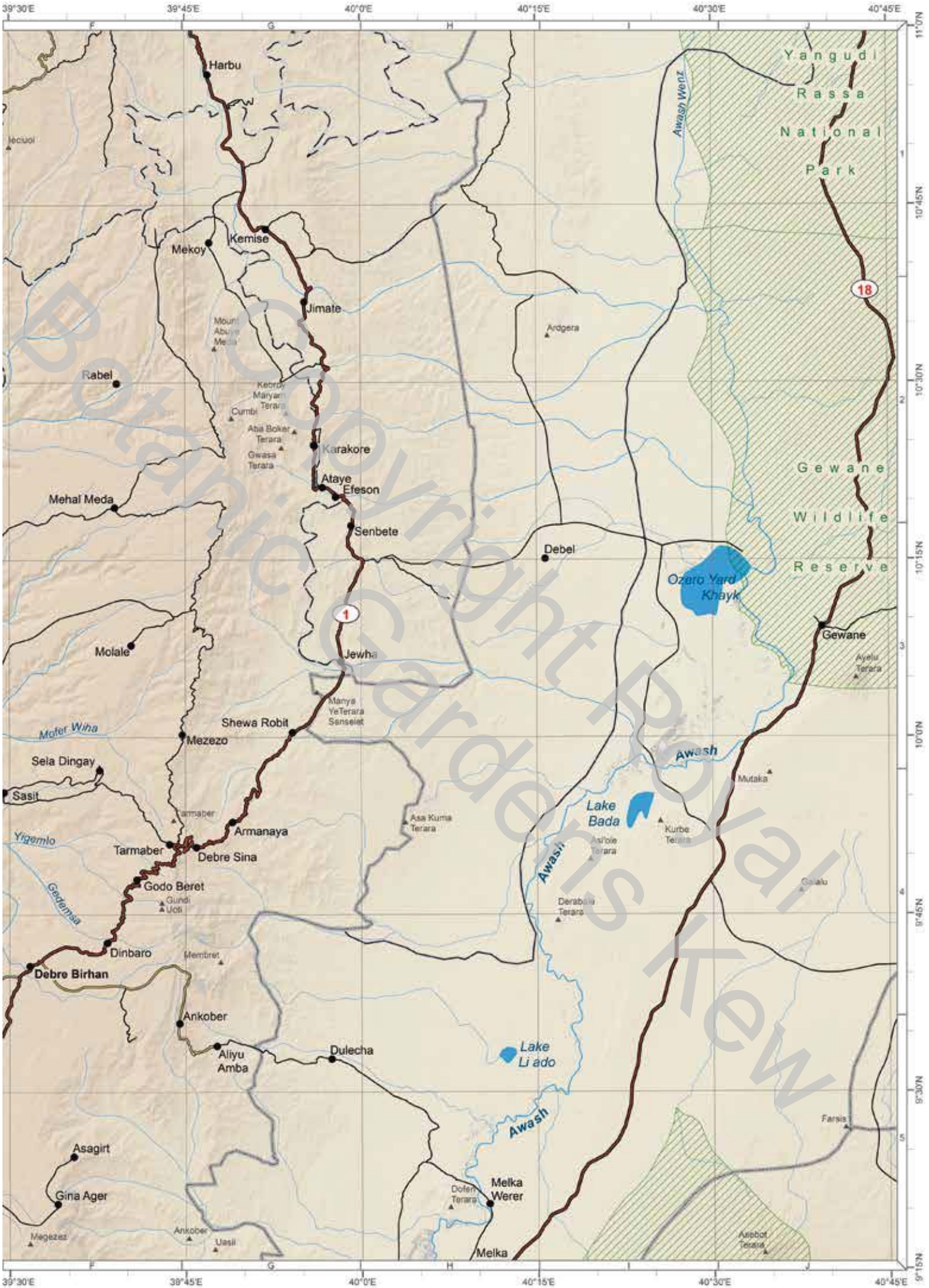
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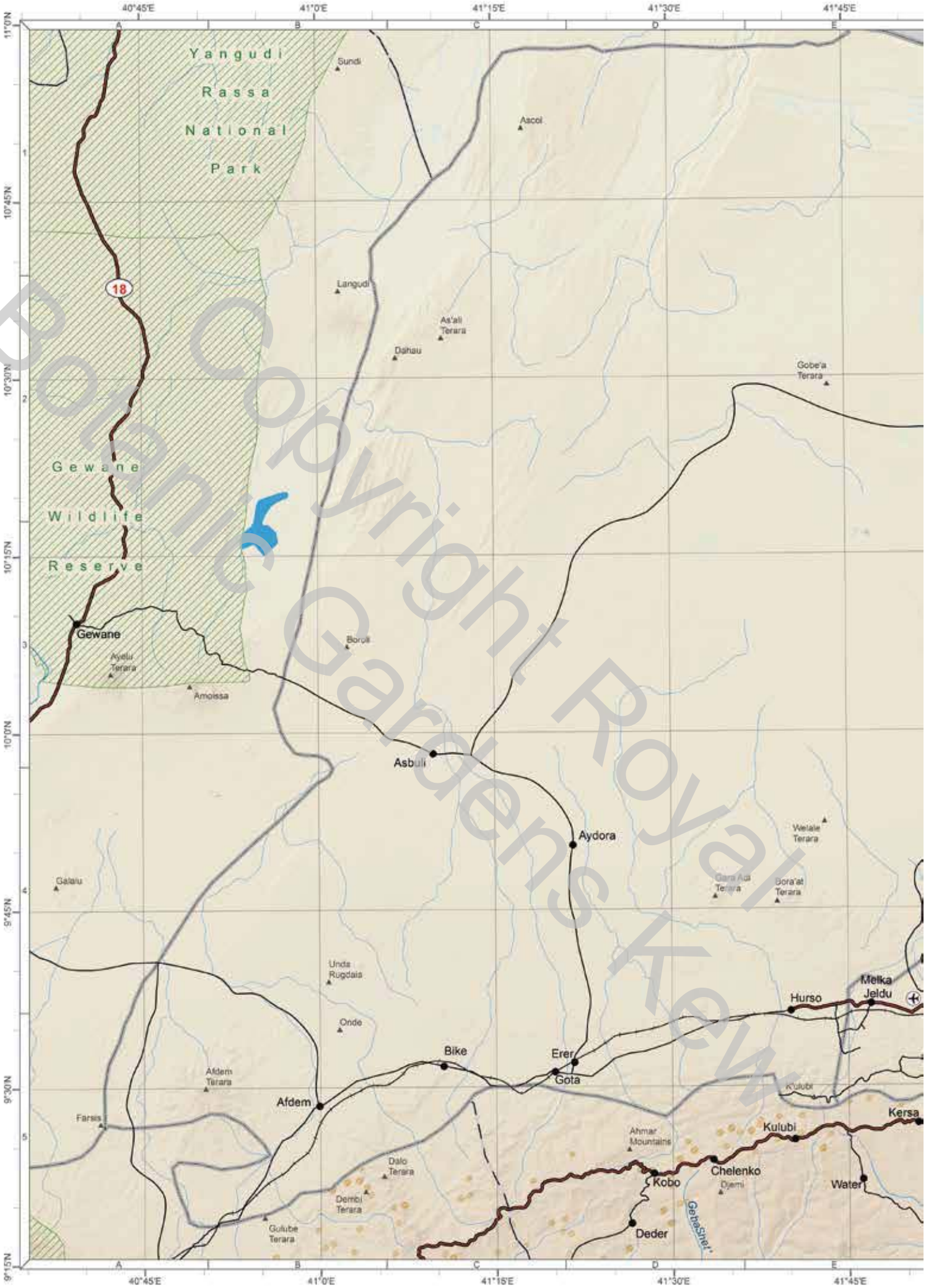
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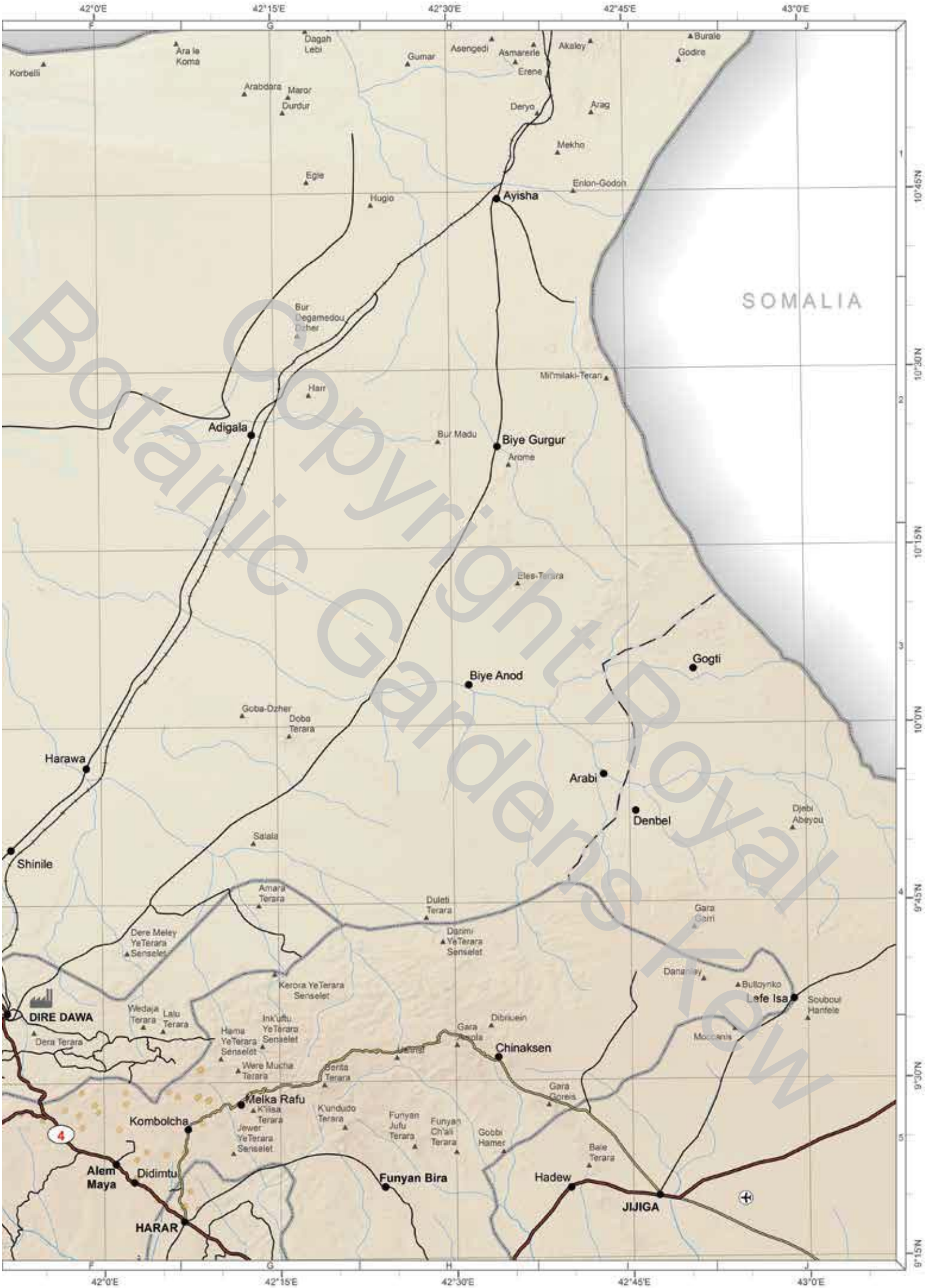
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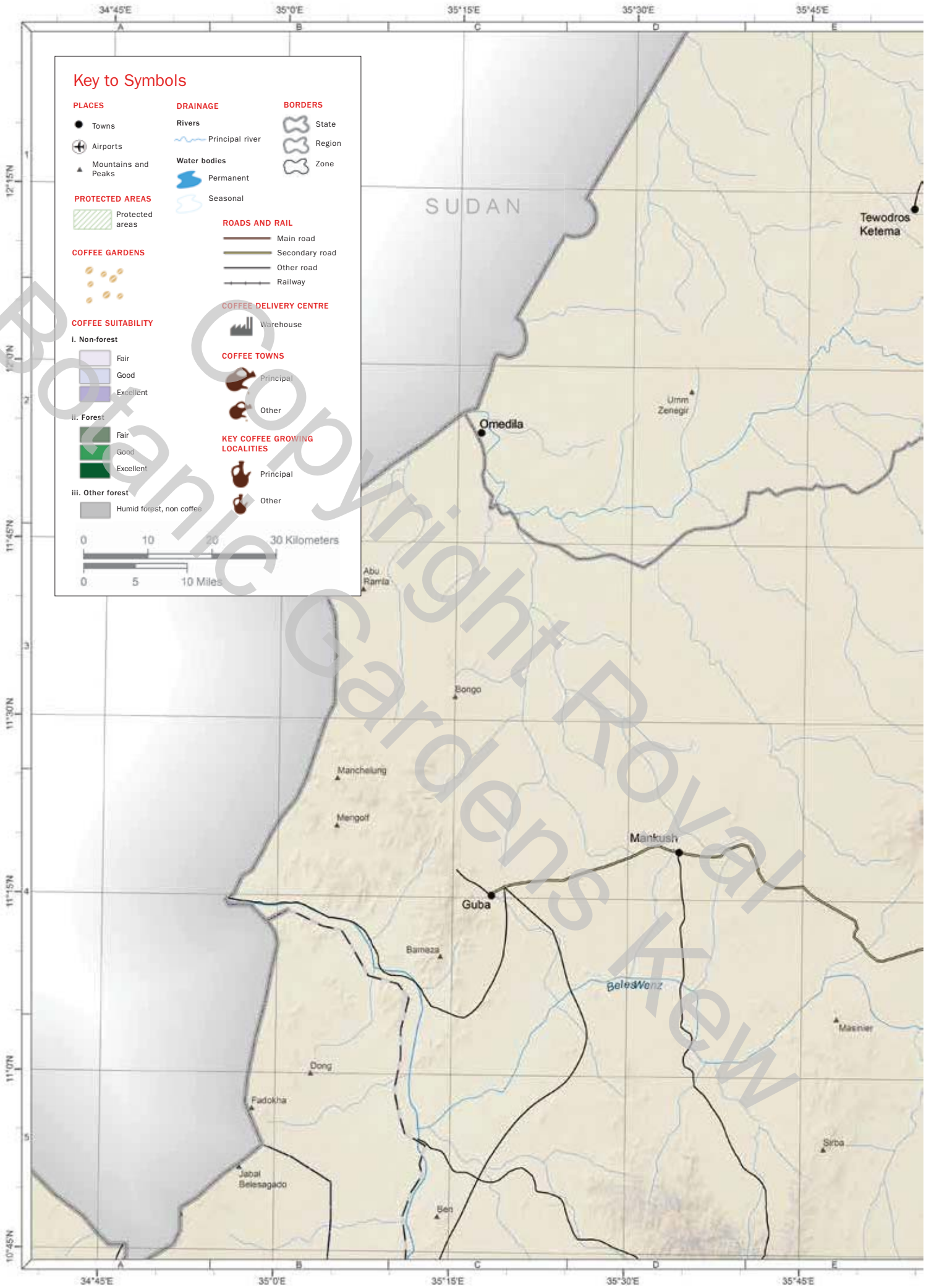
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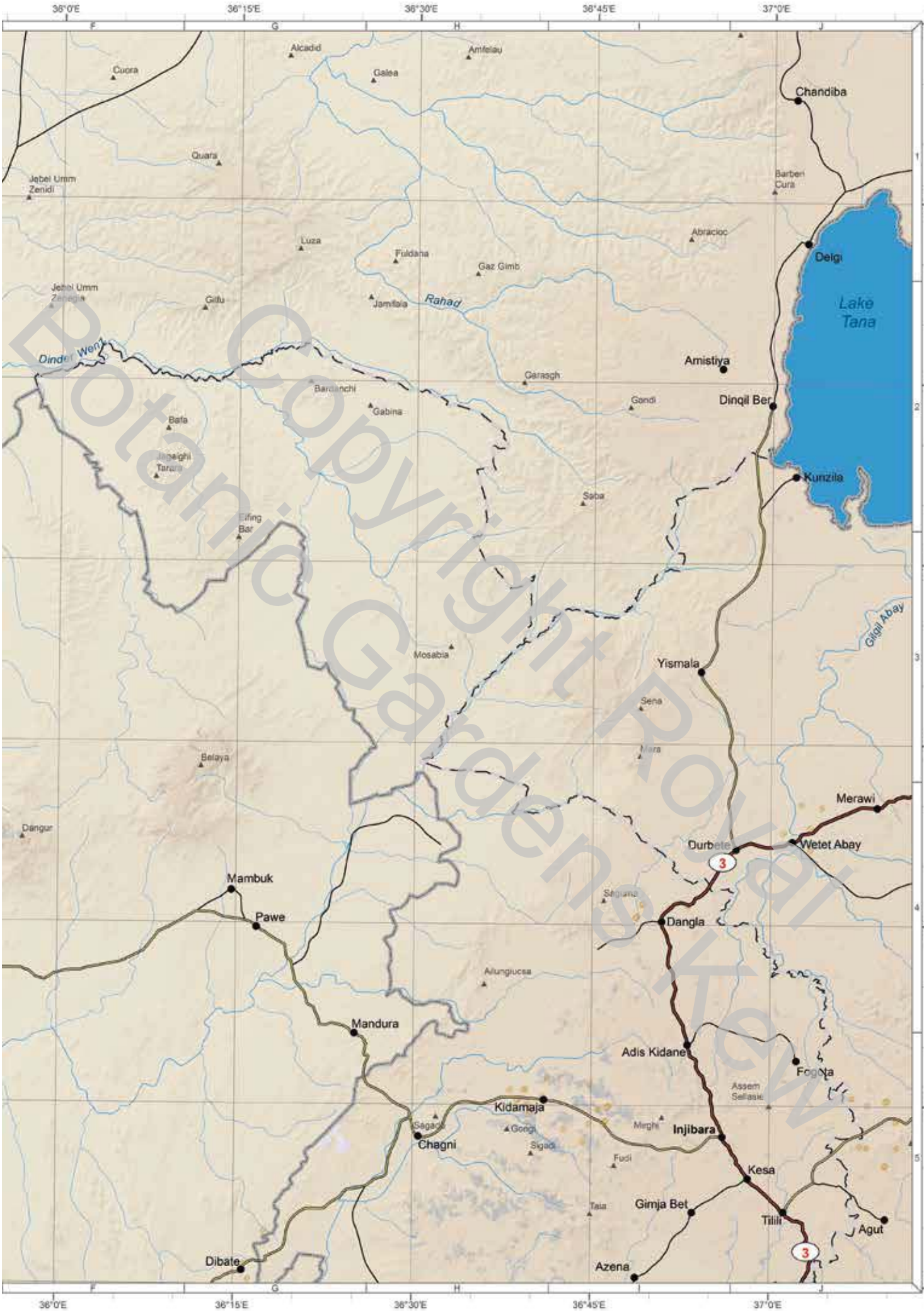
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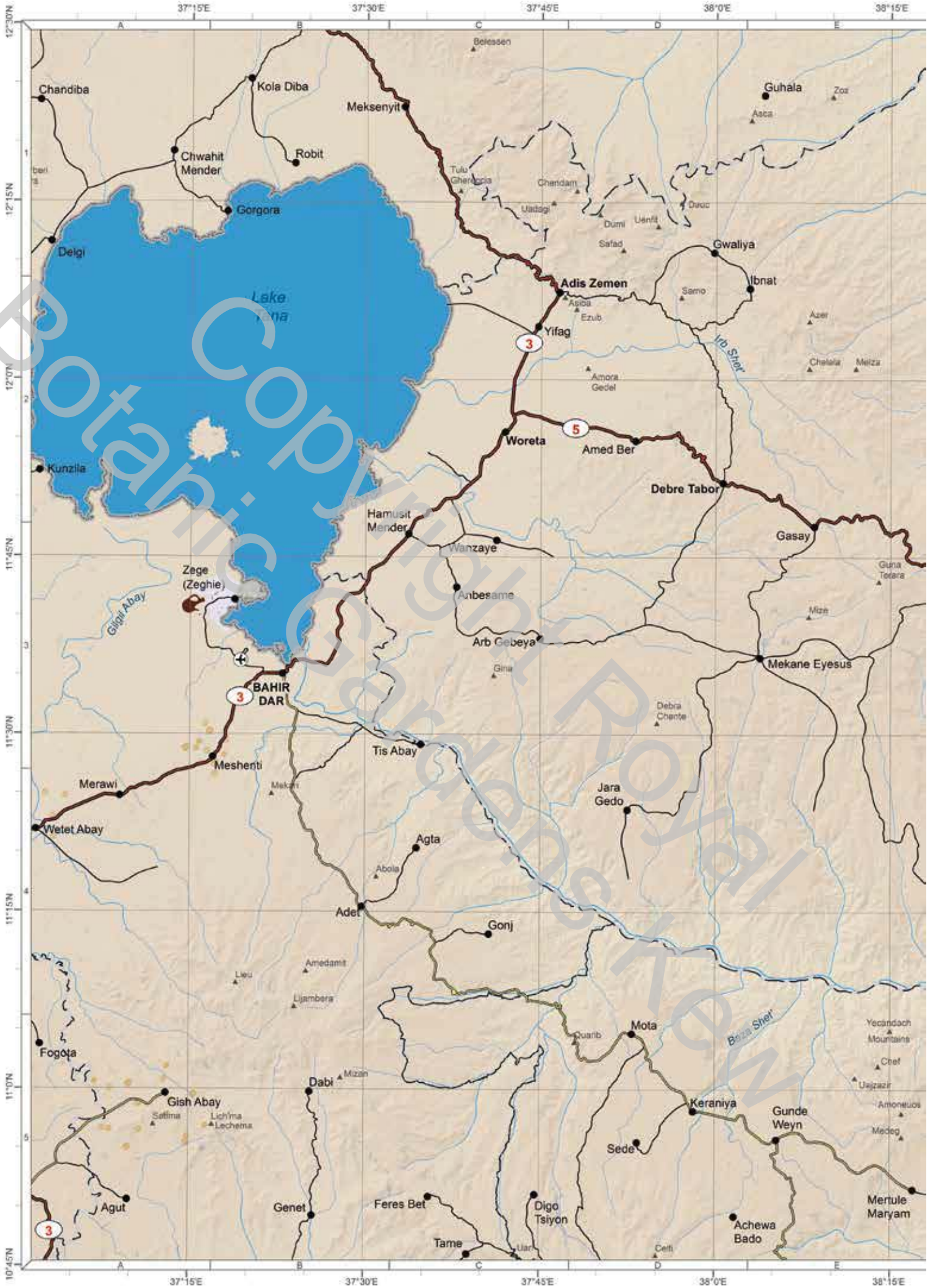
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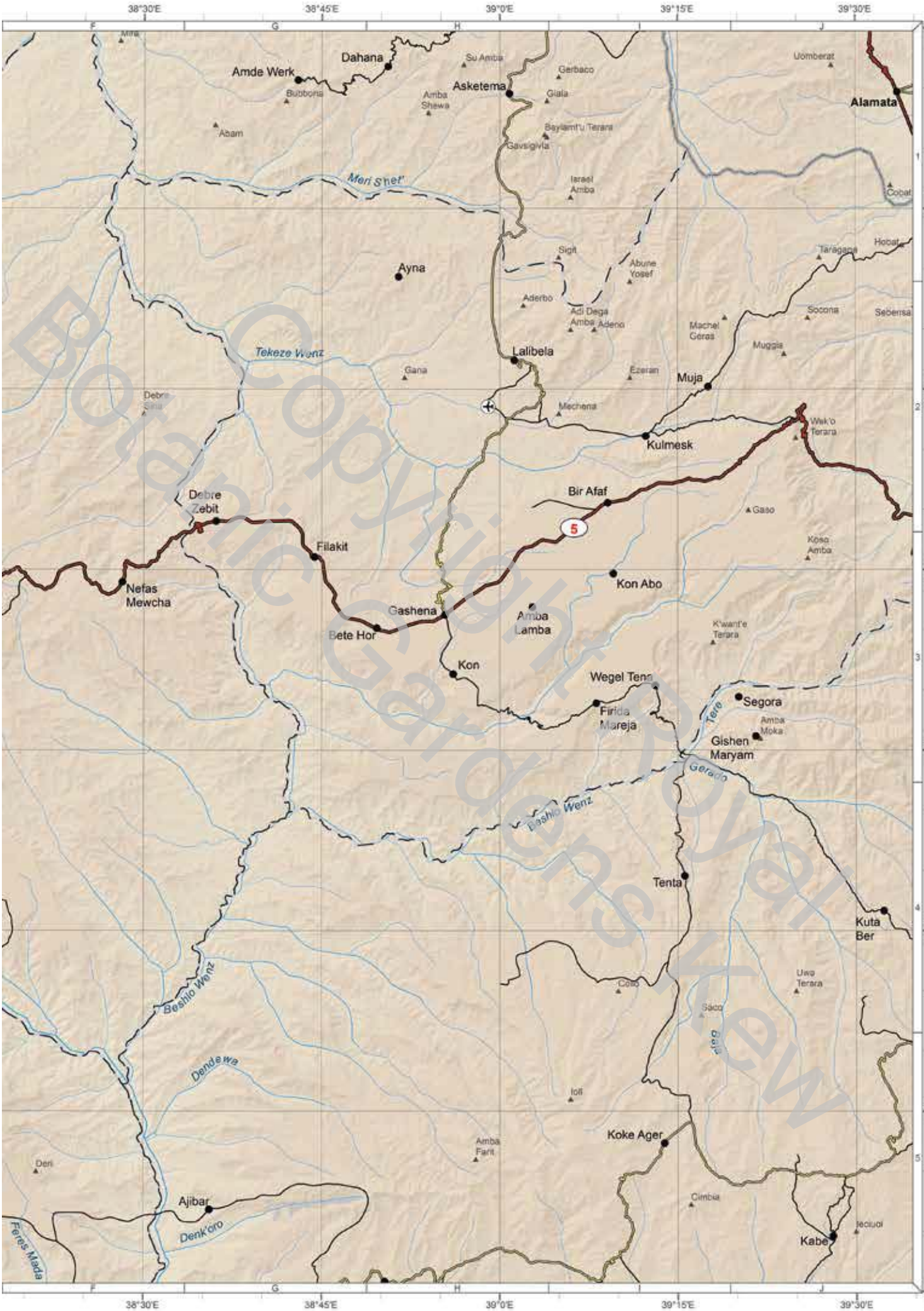
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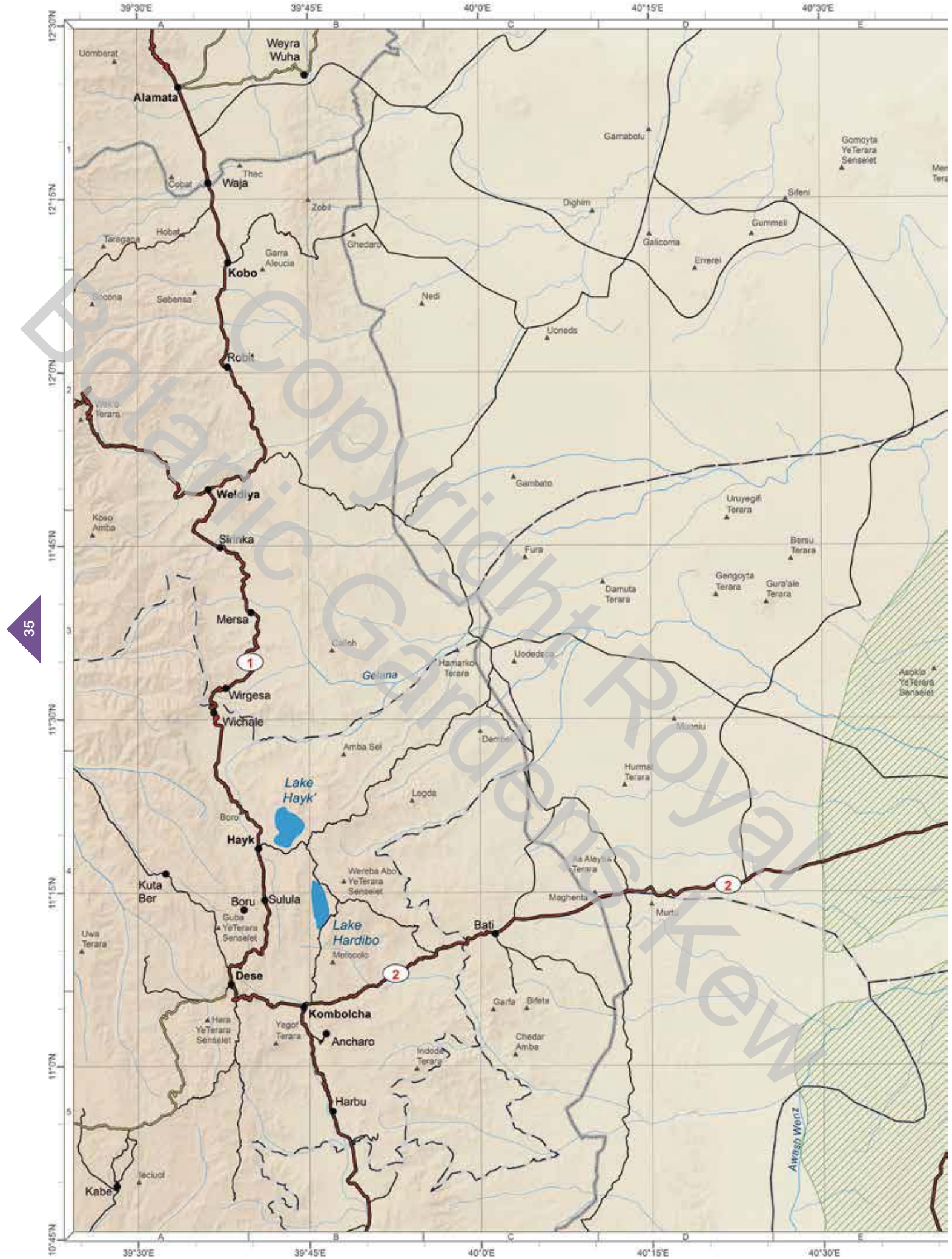
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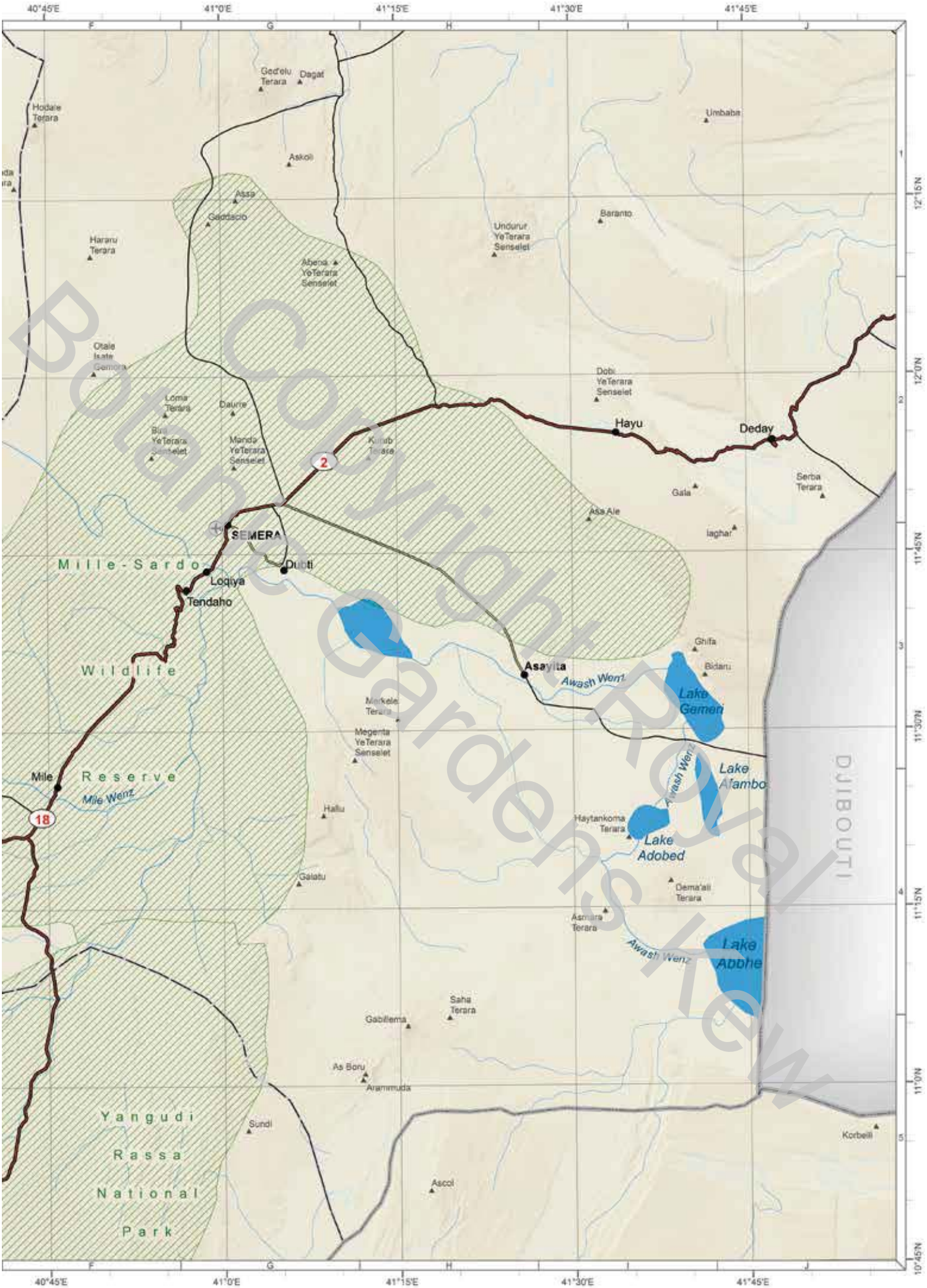
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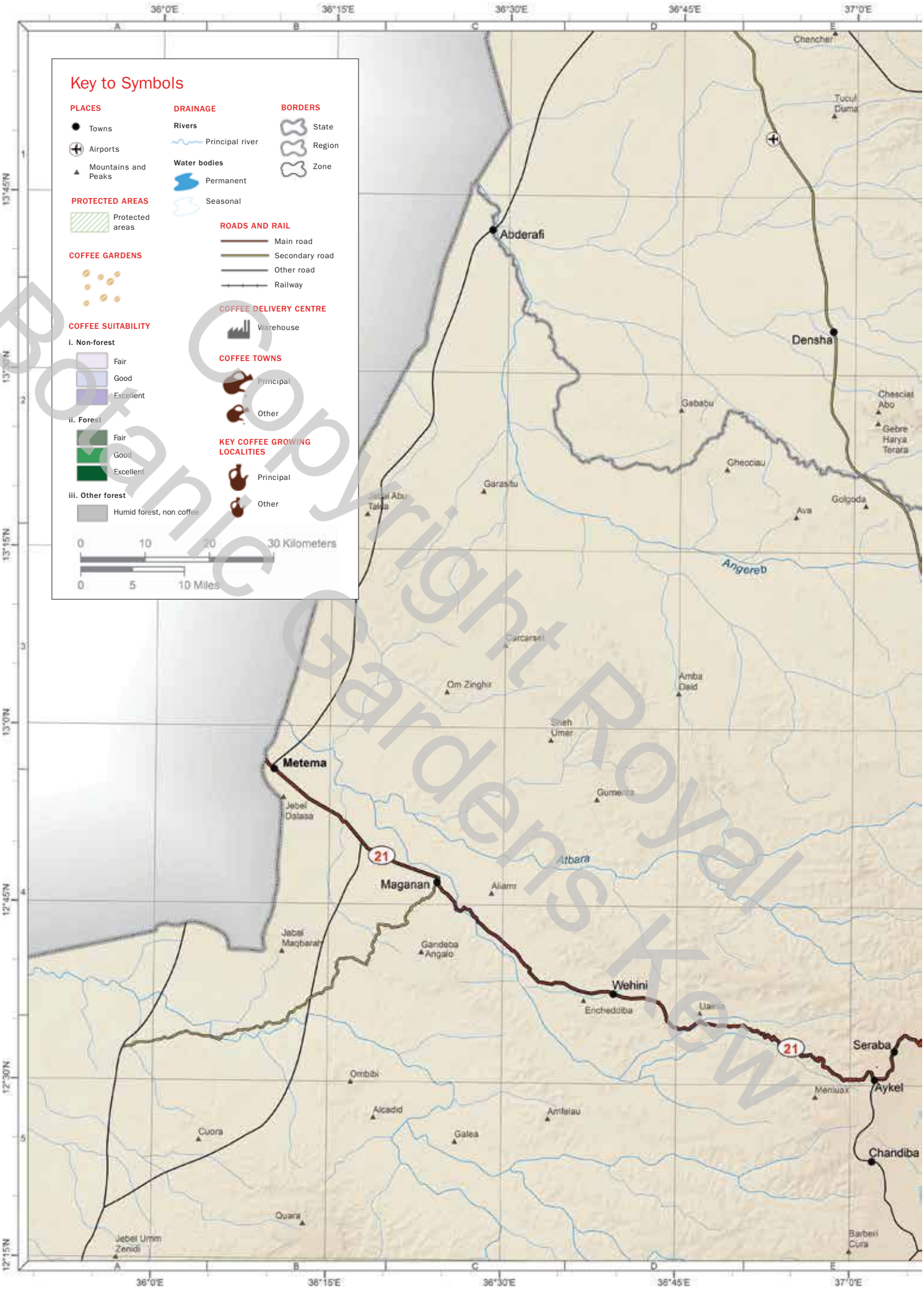
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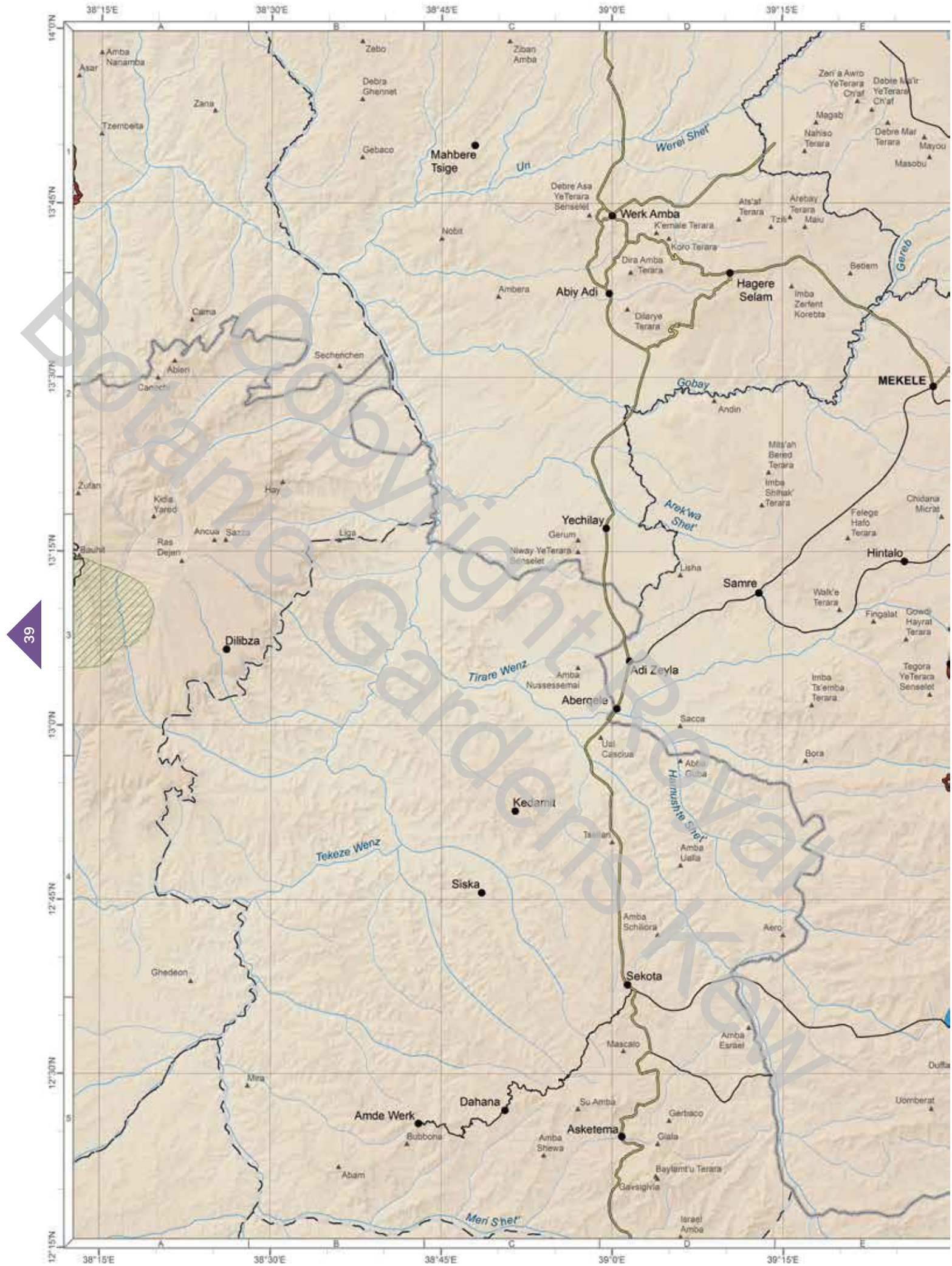
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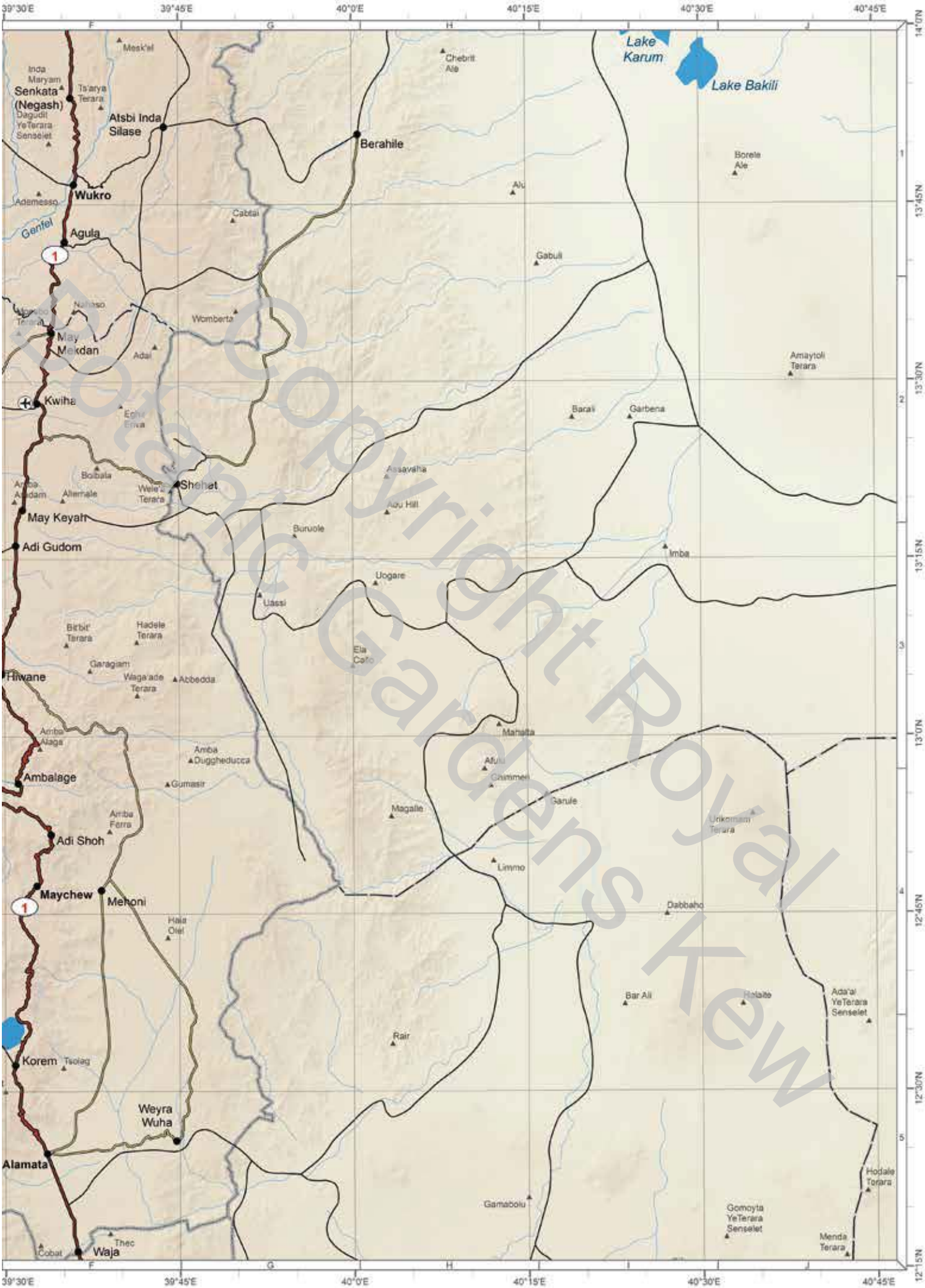
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Fishing on Lake Awasa, in the Great Rift Valley
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Gazetteer (geographical name index)

This gazetteer includes all the mapped geographical features included in the Atlas (apart from roads and rivers), placed into ten categories: zones; coffee-growing localities; coffee towns; coffee delivery centres; regional capitals; airports; protected areas; major lakes; summits/mountains; and towns/settlements. These names are referenced by Atlas map page number, alpha-numeric grid reference, region, zone and the latitude and longitude in degrees and minutes. The alpha-numeric grid reference refers to the letter, A to J (on the bottom of the facing pages) and the number 1 to 5 (on the side of the page).

Zones (administrative) are indicated by page number only, to provide an approximate indication of location; many of the zones span two or more pages. Page numbers and the specific names are given in bold, and zones are in italics. Regions are given in roman without bold or italics. In the gazetteer of towns/settlements, regional capitals are given in upper case (e.g. ASOSA).

Example

Page	Grid	Town	Region	Zone	Coordinates
10	D1	**Jimma**	Oromia	*Jimma*	7°40'N 36°50'E

The town of **Jimma** can be found in the Atlas on page **10**, at grid reference D1. The geographical coordinates 7°40'N 36°50'E can be used to locate this town to an accuracy of approximately 1km. Jimma is a town of the Oromia Region of the *Jimma* (administrative) zone.

Zones

7	***Afder***	Somali
8	***Agnuak***	Gambella
11	***Alaba***	SNNPR
21	***Arsi***	Oromia
24	***Asosa***	Benishangul Gumuz
33	***Awi/Agew***	Amhara
13	***Bale***	Oromia
3	***Basketo***	SNNPR
2	***Bench Maji***	SNNPR
4	***Borena***	Oromia
40	***Central***	Tigray
10	***Dawro***	SNNPR
30	***Dire Dawa***	Dire Dawa
Not in Atlas	***Doolo***	Somali
27	***East Gojam***	Amhara
22	***East Hararge***	Oromia
20	***East Shewa***	Oromia
18	***East Wellega***	Oromia
41	***Eastern***	Tigray
23	***Fafan***	Somali
4	***Gamo Gofa***	SNNPR
4	***Gedio (Gedeo)***	SNNPR
5	***Guji***	Oromia
19	***Gurage***	SNNPR
11	***Hadiya***	SNNPR
23	***Hareri***	Hareri
27	***Horo Guduru***	Oromia
17	***Ilubabor***	Oromia
23	***Jarar***	Somali
10	***Jimma***	Oromia
10	***Kaffa***	SNNPR
17	***Kelem Wellega***	Oromia
25	***Kemashi***	Benishangul Gumuz
10	***Konta***	SNNPR
Not in Atlas	***Korahe***	Somali
11	***Kembata Tembaro***	SNNPR
6	***Liben***	Somali
9	***Majang***	Gambella
32	***Metekel***	Benishangul Gumuz
15	***Nogob***	Somali
38	***North Gonder***	Amhara
28	***North Shewa (R3)***	Amhara
28	***North Shewa (R4)***	Oromia
39	***North Western***	Tigray
35	***North Wollo***	Amhara
16	***Nuer***	Gambella
29	***Oromia***	Amhara
20	***Region 14***	Addis Ababa
4	***Segen Peoples'***	SNNPR
11	***Selti***	SNNPR
15	***Shabelle***	Somali
9	***Sheka***	SNNPR
12	***Sidama***	SNNPR
30	***Siti***	Somali
34	***South Gonder***	Amhara
3	***South Omo***	SNNPR
19	***South West Shewa***	Oromia
28	***South Wollo***	Amhara
40	***Southern***	Tigray
36	***Special Woreda***	Amhara
40	***Wag Himra***	Amhara
12	***West Arsi***	Oromia
34	***West Gojam***	Amhara
22	***West Hararge***	Oromia
19	***West Shewa***	Oromia
17	***West Wellega***	Oromia
39	***Western***	Tigray
11	***Wolayita***	SNNPR
11	***Yem***	SNNPR
37	***Awsi (Zone 1)***	Afar
41	***Kilbati (Zone 2)***	Afar
29	***Gabi (Zone 3)***	Afar
36	***Fenti (Zone 4)***	Afar
29	***Hari (Zone 5)***	Afar

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Coffee-growing localities

5	F2	**Guji**	Oromia	*Guji*	5°52'N 38°29'E
10	B3	**Kaffa**	SNNPR	*Kaffa*	7°15'N 36°7'E
18	D5	**Limu**	Oromia	*Jimma*	7°55'N 36°51'E
13	F5	**Bale (Harenna)**	Oromia	*Bale*	6°31'N 39°44'E
12	C5	**Bensa**	SNNPR	*Sidama*	6°29'N 38°51'E
12	B5	**Bona Zuria**	SNNPR	*Sidama*	6°30'N 38°42'E
10	C1	**Gera**	Oromia	*Jimma*	7°47'N 36°26'E
9	G4	**Gura Ferda**	SNNPR	*Bench Maji*	6°50'N 35°5'E
4	E2	**Kochere**	SNNPR	*Gedio*	6°5'N 38°13'E
9	G2	**Mezhenger Godere)**	Gambella	*Majang*	7°19'N 35°12'E
9	H3	**Sheko**	SNNPR	*Bench Maji*	7°5'N 35°23'E
12	D5	**W. Arsi (Nansebo)**	SNNPR	*Sidama*	6°28'N 39°5'E
12	A4	**Wonsho**	SNNPR	*Sidama*	6°43'N 38°28'E

Coffee towns

10	C1	**Agaro**	Oromia	*Jimma*	7°51'N 36°35'E
12	A4	**Aleta Wendo**	SNNPR	*Sidama*	6°36'N 38°25'E
10	B3	**Anderacha**	SNNPR	*Kaffa*	7°12'N 36°16'E
22	B2	**Asbe Teferi**	Oromia	*West Hararge*	9°4'N 40°51'E
9	H4	**Bebeka**	SNNPR	*Bench Maji*	6°51'N 35°20'E
22	E2	**Bedeno**	Oromia	*East Hararge*	9°6'N 41°37'E
4	B4	**Bekawile (Konso)**	SNNPR	*Segen Peoples'*	5°20'N 37°26'E
10	B3	**Bonga**	SNNPR	*Kaffa*	7°16'N 36°15'E
25	I2	**Debre Zeyit (Wembera)**	Benishangul Gumuz	*Metekel*	10°37'N 35°39'E
27	F1	**Finote Selam**	Amhara	*West Gojam*	10°40'N 37°15'E
16	E2	**Garigeda**	Oromia	*Kelem Wellega*	8°46'N 34°39'E
21	J2	**Gelemso**	Oromia	*West Hararge*	8°48'N 40°30'E
9	H5	**Gesha**	SNNPR	*Bench Maji*	6°33'N 35°30'E
17	J1	**Gimbi**	Oromia	*West Wellega*	9°10'N 35°50'E
21	H4	**Gololcha**	Oromia	*Arsi*	8°11'N 40°3'E
17	H4	**Gore**	Oromia	*Ilubabor*	8°9'N 35°32'E
22	C1	**Hirna**	Oromia	*West Hararge*	9°13'N 41°6'E
10	D1	**Jimma**	Oromia	*Jimma*	7°40'N 36°50'E
2	D1	**Maji**	SNNPR	*Bench Maji*	6°10'N 35°35'E
21	I3	**Mechara**	Oromia	*West Hararge*	8°36'N 40°20'E
22	C2	**Mesela**	Oromia	*West Hararge*	9°5'N 41°10'E
17	I4	**Metu**	Oromia	*Ilubabor*	8°18'N 35°34'E
9	I3	**Mizan Teferi**	SNNPR	*Bench Maji*	7°00'N 35°25'E
16	E3	**Sedi (Ashi)**	Oromia	*Kelem Wellega*	8°39'N 34°40'E
9	H2	**Tepi**	Gambella	*Majang*	7°12'N 35°25'E
4	E1	**Wenago**	Oromia	*Borena*	6°18'N 38°15'E
17	J4	**Yayu**	Oromia	*Ilubabor*	8°20'N 35°49'E
12	A4	**Yirga Alem**	SNNPR	*Sidama*	6°44'N 38°24'E
4	E1	**Yirgacheffe**	Oromia	*Borena*	6°9'N 38°11'E
34	B3	**Zege (Zeghie)**	Amhara	*West Gojam*	11°41'N 37°19'E

Coffee delivery centres

20	C2	**Addis Ababa**	Addis Ababa	*Region 14*	9°0'N 38°46'E
18	C3	**Bedele**	Oromia	*Ilubabor*	8°27'N 36°21'E
10	B3	**Bonga**	SNNPR	*Kaffa*	7°17'N 36°15'E
12	A5	**Dilla**	Oromia	*Borena*	6°24'N 38°18'E
31	F4	**Dire Dawa**	Dire Dawa	*Dire Dawa*	9°35'N 41°51'E
17	J1	**Gimbi**	Oromia	*West Wellega*	9°10'N 35°50'E
12	B3	**Hawassa**	SNNPR	*Sidama*	7°2'N 38°29'E
10	D1	**Jimma**	Oromia	*Jimma*	7°40'N 36°50'E
11	H4	**Soddo**	SNNPR	*Wolayita*	6°51'N 37°45'E

Regional capitals

20	C2	**Addis Ababa (Finfine)**	Addis Ababa/ Oromia	*Region 14*	9°1'N 38°45'E
24	E3	**Asosa**	Benishangul Gumuz	*Asosa*	10°3'N 34°32'E
34	B3	**Bahir Dar**	Amhara	*West Gojam*	11°35'N 37°22'E
31	F4	**Dire Dawa**	Dire Dawa	*Dire Dawa*	9°35'N 41°51'E
16	E4	**Gambela**	Gambella	*Agnuak*	8°15'N 34 °35'E
23	G1	**Harar**	Hareri	*Hareri*	9°18'N 42°7'E
12	B3	**Hawassa**	SNNPR	*Sidama*	7°2'N 38°29'E
23	I1	**Jijiga (Jigjiga)**	Somali	*Fafan*	9°20'N 42°47'E
40	E2	**Mekele**	Tigray	*Southern*	13°29'N 39°28'E
37	G3	**Semera**	Afar	*Awsi (Zone 1)*	11°47'N 41°0'E

Airports

20	C2	**Addis Ababa**	Addis Ababa	*Region 14*	8°58'N 38°47'E
4	C2	**Arba Minch**	SNNPR	*Gamo Gofa*	6°2'N 37°35'E
24	E3	**Assosa**	Benishangul Gumuz	*Asosa*	10°1'N 34°34'E
34	B3	**Bahir Dar**	Amhara	*West Gojam*	11°36'N 37°19'E
31	F4	**Dire Dawa**	Dire Dawa	*Dire Dawa*	9°37'N 41°51'E
16	E4	**Gambela**	Gambella	*Agnuak*	8°7'N 34°33'E
39	G5	**Gonder**	Amhara	*North Gonder*	12°30'N 37°25'E
38	E1	**Humera**	Tigray	*Western*	13°49'N 36°54'E
23	J1	**Jijiga**	Somali	*Fafan*	9°19'N 42°54'E
10	D1	**Jimma**	Oromia	*Jimma*	7°40'N 36°48'E
35	H2	**Lalibela**	Amhara	*North Wollo*	11°58'N 38°59'E
41	F2	**Mekele**	Tigray	*Southern*	13°28'N 39°31'E
13	H3	**Robe (Goba)**	Oromia	*Bale*	7°7'N 40°2'E
37	G3	**Semera**	Afar	*Awsi (Zone 1)*	11°47'N 40°59'E

Protected areas

19	G5	**Abelti Gibie National Forest Priority Area**	Oromia	*Jimma*	8°3'N 37°34'E
12	B2	**Abijatta-Shalla Lakes National Park**	Oromia	*West Arsi*	7°32'N 38°31'E
21	I1	**Alledeghi Wildlife Reserve**	Oromia	*West Hararge*	9°10'N 40°26'E
21	H2	**Awash National Park**	Oromia	*East Shewa*	8°54'N 40°2'E
21	G2	**Awash West Wildlife Reserve**	Oromia	*East Shewa*	8°58'N 39°51'E
13	F4	**Bale Wildlife Reserve**	Oromia	*West Arsi*	6°55'N 39°43'E
13	F4	**Bale Mountains National Park**	Oromia	*West Arsi*	6°55'N 39°40'E
3	I5	**Chelbi Wildlife Reserve**	SNNPR	*South Omo*	5°00'N 36°47'E
16	C5	**Gambella National Park**	Gambella	*Agnuak*	7°57'N 34°7'E
30	A2	**Gewane Wildlife Reserve**	Afar	*Gabi (Zone 3)*	10°24'N 40°42'E
10	A2	**Kaffa UNESCO-MAB Biosphere Reserve**	SNNPR	*Kaffa*	7°25'N 35°56'E
3	G3	**Mago National Park**	SNNPR	*South Omo*	5°32'N 36°15'E
37	G3	**Mille-Sardo Wildlife Reserve**	Afar	*Awsi (Zone 1)*	11°41'N 40°59'E
4	D2	**Nechisar National Park**	Oromia	*Borena*	5°59'N 37°53'E
2	E2	**Omo National Park**	SNNPR	*Bench Maji*	5°55'N 35°45'E
39	H1	**Shire Wildlife Reserve**	Tigray	*North Western*	13°56'N 37°45'E
39	J3	**Simien Mountains**	Amhara	*North Gonder*	13°9'N 38°10'E
39	I3	**Simien National Park**	Amhara	*North Gonder*	13°15'N 38°5'E
3	F2	**Tama Wildlife Reserve**	SNNPR	*South Omo*	5°57'N 36°4'E
5	G5	**Yabello Wildlife Sanctuary**	Oromia	*Borena*	4°47'N 38°30'
37	F5	**Yangudi Rassa National Park**	Afar	*Gabi (Zone 3)*	10°57'N 40°46'E
17	J4	**Yayu UNESCO-MAB Biosphere Reserve**	Oromia	*Ilubabor*	8°26'N 35°48'E

Major lakes

20	B2	**Aba-Samuel Reservoir**	Oromia	*South West Shewa*	8°49'N 38°42'E
20	A5	**Abay Hayk'**	SNNPR	*Selti*	7°56'N 38°21'E
19	I2	**Dendi Hayk'**	Oromia	*West Shewa*	8°50'N 38°0'E
27	F5	**Fincha-a Reservoir**	Oromia	*Horo Guduru*	9°28'N 37°12'E
11	H5	**Lake Abaya**	SNNPR	*Gamo Gofa*	6°20'N 37°50'E
37	J4	**Lake Abbhe**	Afar	*Awsi (Zone 1)*	11°9'N 41°45'E
12	B2	**Lake Abiyala**	Oromia	*West Arsi*	7°36'N 38°35'E
37	I4	**Lake Adobed**	Afar	*Awsi (Zone 1)*	11°22'N 41°36'E
37	I4	**Lake Afambo**	Afar	*Awsi (Zone 1)*	11°24'N 41°41'E
12	A3	**Lake Awasa (Hawassa)**	SNNPR	*Sidama*	7°3'N 38°26'E
29	I4	**Lake Bada**	Afar	*Gabi (Zone 3)*	9°54'N 40°23'E
41	I1	**Lake Bakili**	Afar	*Kilbati (Zone 2)*	13°56'N 40°30'E
21	G2	**Lake Basaka**	Oromia	*East Shewa*	8°52'N 39°52'E
4	B2	**Lake Chamo**	SNNPR	*Gamo Gofa*	5°50'N 37°33'E
20	D3	**Lake Chelekleka**	Oromia	*East Shewa*	8°46'N 38°58'E
12	B3	**Lake Dabashi**	SNNPR	*Sidama*	7°5'N 38°33'E
37	I3	**Lake Gemeri**	Afar	*Awsi (Zone 1)*	11°32'N 41°40'E
36	B4	**Lake Hardibo**	Amhara	*South Wollo*	11°14'N 39°46'E

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36	B4	**Lake Hayk**	Amhara	*South Wollo*	11°21'N 39°43'E
41	I1	**Lake Karum (Assale)**	Afar	*Kilbati (Zone 2)*	13°59'N 40°27'E
20	D4	**Lake Koka**	Oromia	*East Shewa*	8°23'N 39°4'E
12	C2	**Lake Langano**	Oromia	*West Arsi*	7°35'N 38°45'E
29	H5	**Lake Liado**	Afar	*Gabi (Zone 3)*	9°33'N 40°12'E
12	B2	**Lake Shala (Shalla)**	Oromia	*West Arsi*	7°27'N 38°30'E
34	B2	**Lake Tana**	Amhara	*West Gojam/ South Gonder/ North Gonder*	12°0'N 37°18'E
20	C5	**Lake Ziway**	Oromia	*East Shewa*	7°59'N 38°50'E
29	I3	**Ozero Yard Khayk**	Afar	*Gabi (Zone 3)*	10°13'N 40°29'E
19	I3	**Wenchi'i Hayk'**	Oromia	*South West Shewa*	8°47'N 37°53'E

Summits/Mountains

A

29	G2	**Aba Boker Terara**	Amhara	*North Shewa (R3)*	10°26'N 39°54'E
18	C2	**Abalo**	Oromia	*East Wellega*	9°7'N 36°23'E
35	G1	**Abam**	Amhara	*Wag Himra*	12°22'N 38°36'E
12	B3	**Abaro**	Oromia	*West Arsi*	7°7'N 38°38'E
40	D4	**Abba Guba**	Amhara	*Wag Himra*	12°57'N 39°6'E
41	F3	**Abbedda**	Tigray	*Southern*	13°5'N 39°45'E
21	I5	**Abdoy Terara**	Oromia	*Arsi*	8°0'N 40°17'E
37	G1	**Abena YeTerara Senselet**	Afar	*Awsi (Zone 1)*	12°10'N 41°10'E
22	C2	**Abenyo Terara**	Oromia	*West Hararge*	8°57'N 41°9'E
40	J2	**Abieri**	Amhara	*North Gonder*	13°31'N 38°21'E
13	J2	**Abinas**	Oromia	*Bale*	7°29'N 40°30'E
13	I2	**Abol K'asim Terara**	Oromia	*Bale*	7°31'N 40°29'E
34	B4	**Abola**	Amhara	*West Gojam*	11°18'N 37°31'E
33	I1	**Abracioc**	Amhara	*North Gonder*	12°12'N 36°53'E
32	B3	**Abu Ramla**	Benishangul Gumuz	*Metekel*	11°41'N 35°7'E
13	J1	**Abul Casim**	Oromia	*Arsi*	7°43'N 40°31'E
35	I1	**Abune Yosef**	Amhara	*North Wollo*	12°9'N 39°11'E
26	C3	**Abutalla**	Oromia	*East Wellega*	10°10'N 36°25'E
41	J5	**Ada'al YeTerara Senselet**	Afar	*Awsi (Zone 1)*	12°36'N 40°44'E
41	F2	**Adai**	Tigray	*Southern*	13°33'N 39°43'E
22	C1	**Adem Gadi Burk'a Terara**	Oromia	*East Hararge*	9°9'N 41°16'E
41	F1	**Ademesso**	Tigray	*Eastern*	13°46'N 39°33'E
21	H4	**Ademu Terara**	Oromia	Arsi	8°21'N 40°2'E
39	G2	**Adenna**	Tigray	*Western*	13°22'N 37°22'E
35	I2	**Adeno**	Amhara	*North Wollo*	12°5'N 39°8'E
35	H2	**Aderbo**	Amhara	*North Wollo*	12°7'N 39°2'E
10	B3	**Adi**	SNNPR	*Kaffa*	7°2'N 36°9'E
35	I2	**Adi Dega Amba**	Amhara	*North Wollo*	12°5'N 39°6'E
39	G2	**Adi Sicnias**	Tigray	*Western*	13°28'N 37°24'E
41	H2	**Adu Hill**	Afar	*Kilbati (Zone 2)*	13°19'N 40°3'E
19	F1	**Adulan Terara**	Oromia	*West Shewa*	9°13'N 37°10'E
40	E4	**Aero**	Amhara	*Wag Himra*	12°42'N 39°15'E
30	A5	**Afdem Terara**	Somali	*Siti*	9°30'N 40°50'E
16	E4	**Afillu**	Oromia	*Kelem Wellega*	8°25'N 34°39'E
41	H3	**Afulu**	Afar	*Kilbati (Zone 2)*	12°57'N 40°11'E
13	H4	**Agal Terara**	Oromia	*Bale*	6°57'N 40°8'E
10	D4	**Agarri**	SNNPR	*Dawro*	6°55'N 36°50'E
39	F1	**Agazen**	Tigray	*Western*	13°48'N 37°14'E
10	C3	**Aggio**	SNNPR	*Kaffa*	7°9'N 36°37'E
30	D5	**Ahmar Mountains**	Oromia	*East Hararge*	9°25'N 41°26'E
33	H4	**Ailungiucsa**	Amhara	*Awi/Agew*	11°10'N 36°36'E
5	J3	**Aiso**	Oromia	*Guji*	5°29'N 39°26'E
31	I1	**Akaley**	Somali	*Siti*	10°58'N 42°42'E
22	E1	**Ala**	Oromia	*East Hararge*	9°14'N 41°42'E
26	C4	**Alaba Meda**	Oromia	*East Wellega*	9°54'N 36°35'E
12	B3	**Alacha**	Oromia	*West Arsi*	7°7'N 38°34'E
39	G4	**Alama**	Amhara	*North Gonder*	12°38'N 37°22'E
9	I2	**Alamu**	SNNPR	*Kaffa*	7°23'N 35°35'E
8	E4	**Alarra**	Gambella	*Agnuak*	6°49'N 34°37'E
38	B5	**Alcadid**	Amhara	*North Gonder*	12°27'N 36°19'E
19	G4	**Ali**	Oromia	*Jimma*	8°11'N 37°35'E
38	C4	**Aliamr**	Amhara	*North Gonder*	12°46'N 36°29'E
41	F2	**Allemale**	Tigray	*Southern*	13°20'N 39°35'E
41	H1	**Alu**	Afar	*Kilbati (Zone 2)*	13°46'N 40°14'E
9	I3	**Aman Mountains**	SNNPR	*Bench Maji*	7°1'N 35°34'E
3	I3	**Amar**	SNNPR	*South Omo*	5°35'N 36°45'E
31	G4	**Amara Terara**	Dire Dawa	*Dire Dawa*	9°45'N 42°13'E
41	J2	**Amaytoli Terara**	Afar	*Kilbati (Zone 2)*	13°31'N 40°38'E
41	F3	**Amba Alage**	Tigray	*Southern*	12°59'N 39°33'E
39	G3	**Amba Amara**	Amhara	*North Gonder*	13°10'N 37°28'E
41	F2	**Amba Aradam**	Tigray	*Southern*	13°20'N 39°31'E
39	G5	**Amba Auria Azen**	Amhara	*North Gonder*	12°30'N 37°35'E
39	F4	**Amba Balambras**	Amhara	*North Gonder*	12°46'N 37°9'E
39	F2	**Amba Cucoi**	Amhara	*North Gonder*	13°18'N 37°6'E
38	D3	**Amba Daid**	Amhara	*North Gonder*	13°3'N 36°45'E
39	H3	**Amba Dinai**	Amhara	*North Gonder*	13°16'N 37°49'E
41	G3	**Amba Duggheducca**	Tigray	*Southern*	12°58'N 39°46'E
40	D5	**Amba Esrael**	Amhara	*Wag Himra*	12°34'N 39°12'E
35	H5	**Amba Farit**	Amhara	*South Wollo*	10°56'N 38°58'E
41	F4	**Amba Ferra**	Tigray	*Southern*	12°52'N 39°39'E
39	H2	**Amba Ghermie**	Amhara	*North Gonder*	13°22'N 37°48'E
39	F1	**Amba Mahar**	Tigray	*Western*	13°43'N 37°6'E
35	J3	**Amba Moka**	Amhara	*South Wollo*	11°31'N 39°22'E
39	J1	**Amba Nanamba**	Tigray	*North Western*	13°58'N 38°15'E
39	G3	**Amba Nevi**	Amhara	*North Gonder*	13°17'N 37°36'E
40	C3	**Amba Nussessemai**	Amhara	*Wag Himra*	13°5'N 38°57'E
40	D4	**Amba Schiliora**	Amhara	*Wag Himra*	12°42'N 39°4'E
36	B4	**Amba Sel**	Amhara	*South Wollo*	11°27'N 39°48'E
40	C5	**Amba Shewa**	Amhara	*Wag Himra*	12°23'N 38°54'E
40	D4	**Amba Ualla**	Amhara	*Wag Himra*	12°48'N 39°6'E
39	G2	**Amba Zaul**	Tigray	*Western*	13°27'N 37°28'E
39	G4	**Ambazza**	Amhara	*North Gonder*	12°44'N 37°32'E
40	C2	**Ambera**	Tigray	*Central*	13°37'N 38°50'E
11	H3	**Ambericho Terara**	SNNPR	*Kembata Tembaro*	7°17'N 37°52'E
34	B4	**Amedamit**	Amhara	*West Gojam*	11°10'N 37°25'E
39	H4	**Amergie**	Amhara	*North Gonder*	12°53'N 37°47'E
38	C5	**Amfelau**	Amhara	*North Gonder*	12°27'N 36°34'E
30	A3	**Amoissa**	Afar	*Gabi (Zone 3)*	10°4'N 40°49'E
34	E5	**Amoneuos**	Amhara	*East Gojam*	10°58'N 38°16'E
27	H2	**Amora**	Amhara	*East Gojam*	10°35'N 37°46'E
34	D2	**Amora Gedel**	Amhara	*South Gonder*	12°1'N 37°49'E
9	H3	**Amora Gedel Terara**	SNNPR	*Bench Maji*	7°7'N 35°29'E
21	F4	**Amut'a Terara**	Oromia	*Arsi*	8°9'N 39°34'E
20	E5	**Ancfola**	Oromia	*Arsi*	8°6'N 39°28'E
39	F5	**Ancher**	Amhara	*North Gonder*	12°36'N 37°9'E
40	A3	**Ancua (Weynobar)**	Amhara	*North Gonder*	13°16'N 38°25'E
40	D2	**Andin**	Tigray	*Southern*	13°28'N 39°9'E
9	H2	**Andracha YeTerara Senselet**	SNNPR	*Sheka*	7°30'N 35°30'E
38	C4	**Angalo**	Amhara	*North Gonder*	12°41'N 36°23'E
39	H3	**Angareb**	Amhara	*North Gonder*	13°3'N 37°37'E
39	I2	**Angher**	Tigray	*North Western*	13°34'N 37°55'E
21	G1	**Ankober**	Amhara	*North Shewa (R3)*	9°18'N 39°45'E
20	C3	**Anole Terara**	Oromia	*East Shewa*	8°29'N 38°51'E
31	F1	**Ara le Koma**	Somali	*Siti*	10°58'N 42°7'E
23	F2	**Arab**	Oromia	*East Hararge*	8°59'N 41°54'E
31	G1	**Arabdara**	Somali	*Siti*	10°54'N 42°13'E
13	J3	**Arabe YeTerara Senselet**	Oromia	*Bale*	7°3'N 40°32'E
13	I2	**Arablig**	Oromia	*Bale*	7°21'N 40°28'E
31	I1	**Arag**	Somali	*Siti*	10°52'N 42°42'E
37	H5	**Arammuda**	Afar	*Awsi (Zone 1)*	11°1'N 41°12'E
12	D4	**Aranna**	Oromia	*West Arsi*	6°40'N 39°0'E
27	H2	**Arat Mekera Kir**	Amhara	*East Gojam*	10°36'N 37°45'E
18	E5	**Araua**	Oromia	*Jimma*	8°6'N 37°4'E
21	I3	**Arba Gugu Terara**	Oromia	*West Hararge*	8°40'N 40°15'E
39	F3	**Arcai**	Amhara	*North Gonder*	13°7'N 37°19'E
7	F1	**Arce**	Oromia	*Bale*	6°10'N 40°40'E
29	I2	**Ardgera**	Afar	*Hari (Zone 5)*	10°34'N 40°16'E
40	E1	**Arebay Terara**	Tigray	*Central*	13°44'N 39°16'E
3	H2	**Argun**	SNNPR	*South Omo*	5°59'N 36°40'E
18	C2	**Arjo**	Oromia	*East Wellega*	8°49'N 36°28'E
26	C5	**Ark'umbe Terara**	Oromia	*East Wellega*	9°32'N 36°28'E
31	H2	**Arome**	Somali	*Siti*	10°22'N 42°35'E
6	B3	**Arsi Cormoso**	Oromia	*Bale*	5°38'N 39°45'E
36	D4	**As Aleyti Terara**	Afar	*Awsi (Zone 1)*	11°18'N 40°11'E
37	H5	**As Boru**	Afar	*Awsi (Zone 1)*	11°1'N 41°12'E
37	I2	**Asa Ale**	Afar	*Awsi (Zone 1)*	11°48'N 41°32'E
29	H4	**Asa Kuma Terara**	Afar	*Hari (Zone 5)*	9°53'N 40°4'E
30	C2	**As'ali Terara**	Somali	*Siti*	10°33'N 41°11'E
39	J1	**Asar**	Tigray	*North Western*	13°56'N 38°13'E

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34	E1	**Asca**	Amhara	*North Gonder*	12°22'N 38°3'E
30	C1	**Ascol**	Somali	*Siti*	10°51'N 41°18'E
21	J1	**Asebot Terara**	Oromia	*West Hararge*	9°16'N 40°34'E
31	H1	**Asengedi**	Somali	*Siti*	10°58'N 42°34'E
34	C2	**Asiba**	Amhara	*South Gonder*	12°7'N 37°47'E
29	I4	**Asi'ole Terara**	Afar	*Gabi (Zone 3)*	9°50'N 40°20'E
37	G1	**Askoli**	Afar	*Awsi (Zone 1)*	12°18'N 41°6'E
37	I4	**Asmara Terara**	Afar	*Awsi (Zone 1)*	11°15'N 41°33'E
31	H1	**Asmarerle**	Somali	*Siti*	10°57'N 42°38'E
36	E3	**Asoklo YeTerara Senselet**	Afar	*Awsi (Zone 1)*	11°34'N 40°40'E
37	G1	**Assa**	Afar	*Awsi (Zone 1)*	12°15'N 41°1'E
41	H2	**Assavaha**	Afar	*Kilbati (Zone 2)*	13°22'N 40°3'E
33	J5	**Assem Sellasie**	Amhara	*Awi/Agew*	11°0'N 37°0'E
39	G2	**Atquaro**	Tigray	*Western*	13°36'N 37°28'E
40	D1	**Ats'af Terara**	Tigray	*Central*	13°44'N 39°11'E
18	D4	**Auangero**	Oromia	*Jimma*	8°19'N 36°47'E
14	C3	**Auatu**	Oromia	*Bale*	7°18'N 41°6'E
7	J1	**Audo Range**	Somali	*Afder*	6°10'N 41°45'E
38	E2	**Ava**	Amhara	*North Gonder*	13°18'N 36°55'E
30	A3	**Ayelu Terara**	Afar	*Gabi (Zone 3)*	10°5'N 40°42'E
13	F1	**Azama**	Oromia	*Arsi*	7°49'N 39°38'E
34	E2	**Azer**	Amhara	*South Gonder*	12°5'N 38°8'E

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20	E5	**Bada**	Oromia	*Arsi*	7°55'N 39°23'E
19	H3	**Badda Rogghie**	Oromia	*West Shewa*	8°43'N 37°41'E
18	E3	**Badda Ummo**	Oromia	*Jimma*	8°30'N 36°54'E
33	F2	**Bafa**	Amhara	*Awi/Agew*	11°56'N 36°9'E
2	B1	**Bai**	SNNPR	*Bench Maji*	6°16'N 35°11'E
10	C4	**Baka**	SNNPR	*Konta*	6°49'N 36°35'E
12	A1	**Balch'i**	SNNPR	*Selti*	7°50'N 38°20'E
3	A5	**Baldo**	Oromia	*Borena*	4°47'N 37°6'E
23	I3	**Bal'-Dzhi**	Oromia	*East Hararge*	8°37'N 42°42'E
31	I5	**Bale Terara**	Somali	*Fafan*	9°23'N 42°41'E
24	E4	**Bambesi**	Benishangul Gumuz	*Asosa*	9°43'N 34°40'E
32	C4	**Bameza**	Benishangul Gumuz	*Metekel*	11°10'N 35°14'E
23	I3	**Ban-Askulle**	Oromia	*East Hararge*	8°31'N 42°49'E
2	D1	**Bangal**	SNNPR	*Bench Maji*	6°11'N 35°33'E
41	I4	**Bar Ali**	Afar	*Fenti (Zone 4)*	12°37'N 40°23'E
41	I2	**Barali**	Afar	*Kilbati (Zone 2)*	13°27'N 40°19'E
12	E4	**Baranta Terara**	Oromia	*West Arsi*	6°47'N 39°27'E
37	I1	**Baranto**	Afar	*Awsi (Zone 1)*	12°13'N 41°33'E
33	J1	**Barberi Cura**	Amhara	*North Gonder*	12°16'N 37°0'E
2	C2	**Barchu**	SNNPR	*Bench Maji*	5°54'N 35°19'E
33	G2	**Bardanchi**	Amhara	*Awi/Agew*	12°0'N 36°21'E
39	F2	**Baridiot**	Tigray	*Western*	13°21'N 37°21'E
7	J1	**Basra**	Somali	*Afder*	6°10'N 41°44'E
13	F4	**Batu**	Oromia	*Bale*	6°55'N 39°44'E
39	J3	**Bauhit (Bwahit)**	Amhara	*North Gonder*	13°15'N 38°13'E
35	H1	**Baylamt'u Terara**	Amhara	*Wag Himra*	12°21'N 39°4'E
19	I1	**Bedat'ina Amba**	Oromia	*West Shewa*	9°18'N 37°56'E
33	G3	**Belaya**	Benishangul Gumuz	*Metekel*	11°28'N 36°12'E
18	E1	**Belbela YeTerara Ch'af**	Oromia	*East Wellega*	9°21'N 37°4'E
21	I3	**Belbeleyti YeTerara Senselet**	Oromia	*West Hararge*	8°48'N 40°27'E
24	E4	**Belbiso**	Benishangul Gumuz	*Asosa*	9°52'N 34°37'E
24	D2	**Beldoesu**	Benishangul Gumuz	*Asosa*	10°19'N 34°23'E
39	H5	**Belessen**	Amhara	*North Gonder*	12°28'N 37°39'E
18	E4	**Belida**	Oromia	*Jimma*	8°24'N 36°58'E
3	H2	**Belio**	SNNPR	*South Omo*	5°54'N 36°30'E
9	F2	**Belo**	Gambella	*Agnuak*	7°22'N 34°51'E
18	A2	**Bendi**	Oromia	*West Wellega*	8°57'N 36°0'E
10	C4	**Benkira**	SNNPR	*Konta*	6°39'N 36°29'E
5	H2	**Berbissa Tuto**	Oromia	*Guji*	6°1'N 38°53'E
20	D1	**Berek Terara**	Oromia	*North Shewa (R4)*	9°13'N 39°0'E
25	G1	**Beri**	Benishangul Gumuz	*Metekel*	10°48'N 35°14'E
21	F3	**Bericha Terara**	Oromia	*East Shewa*	8°37'N 39°31'E
36	E3	**Bersu Terara**	Afar	*Awsi (Zone 1)*	11°44'N 40°27'E
9	F2	**Betagheue**	Gambella	*Agnuak*	7°20'N 34°53'E
40	E1	**Betlem**	Tigray	*Central*	13°39'N 39°21'E
19	F2	**Betuma**	Oromia	*West Shewa*	9°4'N 37°12'E
24	E3	**Bibbio**	Benishangul Gumuz	*Asosa*	10°14'N 34°44'E
37	I3	**Bidaru**	Afar	*Awsi (Zone 1)*	11°35'N 41°41'E
13	F2	**Bidu Bala**	Oromia	*Arsi*	7°30'N 39°40'E
36	C5	**Bifeta**	Amhara	*Oromia*	11°5'N 40°4'E
19	H2	**Bifti YeTerara Ch'af**	Oromia	*West Shewa*	9°1'N 37°43'E
22	A5	**Bilik'a Terara**	Oromia	*West Hararge*	8°2'N 40°49'E
37	F2	**Bira YeTerara Senselet**	Afar	*Awsi (Zone 1)*	11°53'N 40°54'E
23	I2	**Birdid**	Oromia	*East Hararge*	8°48'N 42°46'E
41	F3	**Bit'bit'Terara**	Tigray	*Southern*	13°8'N 39°35'E
11	H2	**Bobigia**	SNNPR	*Hadiya*	7°23'N 37°44'E
18	E3	**Boca**	Oromia	*Jimma*	8°35'N 37°5'E
20	E2	**Boccan**	Amhara	*North Shewa (R3)*	8°53'N 39°16'E
9	G4	**Bocol**	Gambella	*Agnuak*	6°42'N 35°6'E
3	G3	**Bodu**	SNNPR	*South Omo*	5°46'N 36°14'E
18	B4	**Boia**	Oromia	*Ilubabor*	8°17'N 36°20'E
19	H2	**Bola**	Oromia	*West Shewa*	8°49'N 37°42'E
19	G2	**Bola Rogghie**	Oromia	*West Shewa*	8°54'N 37°37'E
41	F2	**Bolbala**	Tigray	*Southern*	13°23'N 39°38'E
19	I2	**Bole Terara**	Oromia	*West Shewa*	9°2'N 38°4'E
11	G3	**Bolosso**	SNNPR	*Wolayita*	7°3'N 37°36'E
32	C3	**Bongo**	Benishangul Gumuz	*Metekel*	11°32'N 35°15'E
12	C5	**Bonsa Terara**	SNNPR	*Sidama*	6°29'N 38°47'E
40	E4	**Bora**	Tigray	*Southern*	12°57'N 39°17'E
26	E4	**Bora Terara**	Oromia	*East Wellega*	9°56'N 36°53'E
30	E4	**Bora'at Terara**	Somali	*Siti*	9°46'N 41°39'E
26	D2	**Boramu**	Amhara	*West Gojam*	10°25'N 36°42'E
10	E1	**Bore**	Oromia	*Jimma*	7°52'N 37°2'E
41	J1	**Borele Ale**	Afar	*Kilbati (Zone 2)*	13°48'N 40°33'E
36	A4	**Boro**	Amhara	*South Wollo*	11°22'N 39°39'E
30	B3	**Boroli**	Somali	*Siti*	10°7'N 41°2'E
21	F4	**Borora**	Oromia	*Arsi*	8°15'N 39°32'E
20	D4	**Borra**	Oromia	*Arsi*	8°16'N 39°2'E
20	E3	**Boru T'oru Terara**	Oromia	*East Shewa*	8°43'N 39°15'E
20	E3	**Boset Terara**	Oromia	*East Shewa*	8°33'N 39°29'E
17	I5	**Bota**	Oromia	*Ilubabor*	7°54'N 35°39'E
19	I2	**Boti**	Oromia	*West Shewa*	8°51'N 38°3'E
19	F5	**Botor**	Oromia	*Jimma*	8°6'N 37°12'E
40	B5	**Bubbona**	Amhara	*Wag Himra*	12°24'N 38°42'E
4	A5	**Bube**	Oromia	*Borena*	4°49'N 37°11'E
11	J2	**Bubisa**	SNNPR	*Alaba*	7°24'N 38°14'E
26	B1	**Bulan**	Benishangul Gumuz	*Metekel*	10°41'N 36°6'E
31	J4	**Bulloynko**	Oromia	*East Hararge*	9°38'N 42°54'E
18	C4	**Bunno**	Oromia	*Ilubabor*	8°20'N 36°30'E
31	G2	**Bur Degamedou Dzher**	Somali	*Siti*	10°33'N 42°17'E
31	H2	**Bur Madu**	Somali	*Siti*	10°24'N 42°29'E
20	C1	**Bura Terara**	Oromia	*North Shewa (R4)*	9°16'N 38°51'E
31	I1	**Burale**	Somali	*Siti*	10°58'N 42°51'E
3	I4	**Burie**	SNNPR	*South Omo*	5°8'N 36°46'E
23	J2	**Bur-Mulale**	Somali	*Fafan*	8°59'N 42°55'E
23	J2	**Bur-Naf**	Somali	*Fafan*	8°55'N 42°57'E
41	G3	**Buruole**	Afar	*Kilbati (Zone 2)*	13°17'N 39°55'E
10	C3	**Butta**	SNNPR	*Kaffa*	7°7'N 36°27'E
10	E5	**Buzzani**	SNNPR	*Gamo Gofa*	6°29'N 36°59'E
39	J3	**Bwahit (Bauhit)**	Amhara	*North Gonder*	13°15'N 38°13'E

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18	D3	**Cabba**	Oromia	*East Wellega*	8°40'N 36°41'E
41	G1	**Cabtai**	Tigray	*Eastern*	13°44'N 39°50'E
4	E5	**Calciati**	Oromia	*Borena*	4°48'N 38°4'E
36	B3	**Calloh**	Amhara	*North Wollo*	11°36'N 39°47'E
40	J2	**Cama**	Tigray	*North Western*	13°35'N 38°23'E
40	J2	**Canechi**	Amhara	*North Gonder*	13°30'N 38°20'E
28	E5	**Caniss**	Amhara	*North Shewa (R3)*	9°26'N 39°28'E
2	C2	**Canta**	SNNPR	*Bench Maji*	6°3'N 35°17'E
38	C3	**Carcarset**	Amhara	*North Gonder*	13°7'N 36°30'E
27	I1	**Carni**	Amhara	*East Gojam*	10°45'N 38°0'E
39	G5	**Carua Mariam**	Amhara	*North Gonder*	12°35'N 37°26'E
19	H3	**Cascio**	Oromia	*South West Shewa*	8°47'N 37°50'E

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11	J3	**Cassi**	Oromia	*West Arsi*	7°10'N 38°18'E
39	F1	**Catri Gua**	Tigray	*Western*	13°47'N 37°19'E
39	F1	**Cefa**	Tigray	*Western*	13°58'N 37°19'E
39	F3	**Celguana**	Amhara	*North Gonder*	13°0'N 37°10'E
25	F3	**Cellalaca**	Benishangul Gumuz	*Asosa*	10°1'N 34°55'E
27	I1	**Celti**	Amhara	*East Gojam*	10°46'N 37°55'E
18	D2	**Ch'alchis Terara**	Oromia	*East Wellega*	9°8'N 36°44'E
3	I3	**Ch'ali Terara**	SNNPR	*South Omo*	5°45'N 36°45'E
3	H4	**Challa**	SNNPR	*South Omo*	5°23'N 36°34'E
41	H1	**Chebrit Ale**	Afar	*Kilbati (Zone 2)*	13°58'N 40°8'E
36	C5	**Chedar Amba**	Amhara	*Oromia*	11°1'N 40°3'E
34	E5	**Chef**	Amhara	*East Gojam*	11°2'N 38°14'E
34	E2	**Chelala**	Amhara	*South Gonder*	12°1'N 38°8'E
19	F2	**Chelia**	Oromia	*West Shewa*	9°6'N 37°19'E
38	E1	**Chencher**	Tigray	*Western*	13°59'N 36°58'E
34	H5	**Chendam**	Amhara	*South Gonder*	12°16'N 37°48'E
13	I2	**Chera**	Oromia	*Bale*	7°27'N 40°15'E
21	J2	**Ch'erch'er**	Oromia	*West Hararge*	8°55'N 40°35'E
39	G4	**Ch'erch'er**	Amhara	*North Gonder*	12°41'N 37°27'E
22	A2	**Ch'erch'er Terara**	Oromia	*West Hararge*	9°0'N 40°48'E
38	E2	**Chesciat Abo**	Tigray	*Western*	13°27'N 37°2'E
39	I1	**Chessad Afoton**	Tigray	*North Western*	13°48'N 38°6'E
2	C2	**Chiare**	SNNPR	*Bench Maji*	6°3'N 35°22'E
40	E3	**Chidana Micrat**	Tigray	*Southern*	13°18'N 39°29'E
12	D2	**Ch'ik'e Terara**	Oromia	*Arsi*	7°30'N 39°1'E
20	E5	**Ch'ilalo Terara**	Oromia	*Arsi*	7°55'N 39°16'E
27	G1	**Ch'ok'e**	Amhara	*West Gojam*	10°45'N 37°35'E
27	H1	**Ch'ok'e Terara**	Amhara	*East Gojam*	10°43'N 37°51'E
25	H3	**Ciababa**	Benishangul Gumuz	*Metekel*	10°13'N 35°22'E
12	A3	**Ciabbi**	Oromia	*West Arsi*	7°11'N 38°26'E
21	F5	**Ciai**	Oromia	*Arsi*	8°2'N 39°31'E
39	G2	**Cialud**	Amhara	*North Gonder*	13°20'N 37°31'E
19	G3	**Ciancio Gefersa**	Oromia	*West Shewa*	8°48'N 37°24'E
39	H3	**Ciarduqua**	Amhara	*North Gonder*	13°15'N 37°39'E
28	E1	**Cimbia**	Amhara	*South Wollo*	10°52'N 39°16'E
25	G3	**Ciono**	Benishangul Gumuz	*Asosa*	9°58'N 35°8'E
16	C3	**Ciuraccia**	Oromia	*Kelem Wellega*	8°44'N 34°15'E
4	C4	**Clarke**	SNNPR	*Segen Peoples'*	5°17'N 37°36'E
36	A1	**Cobat**	Tigray	*Southern*	12°17'N 39°33'E
18	C4	**Codda**	Oromia	*Ilubabor*	8°11'N 36°36'E
20	A3	**Cofla**	Oromia	*South West Shewa*	8°31'N 38°27'E
21	F2	**Cogi**	Amhara	*North Shewa (R3)*	8°52'N 39°38'E
39	F1	**Cola Siba**	Tigray	*Western*	13°39'N 37°15'E
19	G4	**Colbo**	SNNPR	*Gurage*	8°17'N 37°32'E
35	I4	**Collo**	Amhara	*South Wollo*	11°10'N 39°10'E
19	I3	**Combolata**	Oromia	*South West Shewa*	8°33'N 38°3'E
9	G4	**Comeca**	Gambella	*Agnuak*	6°47'N 35°6'E
18	E2	**Conci**	Oromia	*East Wellega*	8°51'N 37°4'E
26	A3	**Corac**	Benishangul Gumuz	*Kemashi*	10°3'N 35°58'E
2	C3	**Corma**	SNNPR	*Bench Maji*	5°45'N 35°21'E
24	E5	**Corosco**	Oromia	*West Wellega*	9°27'N 34°34'E
13	F3	**Cotera**	Oromia	*Bale*	7°4'N 39°42'E
14	A2	**Cubbaio**	Oromia	*Bale*	7°36'N 40°47'E
25	I2	**Culan Sancai**	Benishangul Gumuz	*Metekel*	10°35'N 35°45'E
26	C5	**Cuma**	Oromia	*East Wellega*	9°33'N 36°35'E
29	G2	**Cumbi**	Amhara	*North Shewa (R3)*	10°27'N 39°49'E
6	A4	**Cuntulo**	Oromia	*Guji*	5°25'N 39°38'E
38	A5	**Cuora**	Amhara	*North Gonder*	12°25'N 36°4'E
39	F3	**Curcuana**	Amhara	*North Gonder*	13°0'N 37°10'E
39	F3	**Curcura**	Amhara	*North Gonder*	13°5'N 37°19'E

D

41	I4	**Dabbaho**	Afar	*Fenti (Zone 4)*	12°45'N 40°27'E
21	J5	**Dabe Terara**	Oromia	*West Hararge*	8°4'N 40°34'E
13	H4	**Dabei**	Oromia	*Bale*	6°56'N 40°14'E
27	F4	**Daben Terara**	Oromia	*Horo Guduru*	9°55'N 37°10'E
18	B3	**Dabo Gumbi**	Oromia	*Ilubabor*	8°46'N 36°17'E
7	I5	**Dacai Adade**	Somali	*Afder*	5°5'N 41°30'E
31	G1	**Dagah Lebi**	Somali	*Siti*	10°59'N 42°18'E
37	G1	**Dagat**	Afar	*Awsi (Zone 1)*	12°25'N 41°7'E
39	G2	**Dagua Tafa**	Amhara	*North Gonder*	13°19'N 37°23'E
27	H2	**Daguai**	Amhara	*East Gojam*	10°38'N 37°43'E
41	F1	**Dagudit YeTerara Senselet**	Tigray	*Eastern*	13°50'N 39°34'E
30	C2	**Dahau**	Somali	*Siti*	10°32'N 41°7'E
26	C5	**Dale Terara**	Oromia	*East Wellega*	9°33'N 36°27'E
21	J1	**Daleccia**	Oromia	*West Hararge*	9°14'N 40°40'E
23	G3	**Daleti Afeta Terara**	Oromia	*East Hararge*	8°35'N 42°8'E
18	D1	**Daleti Terara**	Oromia	*East Wellega*	9°16'N 36°41'E
22	B1	**Dalo Terara**	Oromia	*West Hararge*	9°22'N 41°5'E
31	I1	**Damer**	Somali	*Siti*	10°52'N 42°51'E
15	H4	**Damerta**	Somali	*Shabelle*	6°39'N 42°35'E
2	C2	**Dami**	SNNPR	*Bench Maji*	6°6'N 35°24'E
26	A4	**Dami**	Benishangul Gumuz	*Kemashi*	9°48'N 36°5'E
13	I4	**Damole Terara**	Oromia	*Bale*	6°45'N 40°27'E
10	D3	**Damota**	SNNPR	*Konta*	7°3'N 36°39'E
11	H4	**Damota Terara**	SNNPR	*Wolayita*	6°55'N 37°47'E
20	A4	**Damu Terara**	SNNPR	*Gurage*	8°12'N 38°26'E
36	D3	**Damuta Terara**	Afar	*Awsi (Zone 1)*	11°42'N 40°11'E
21	H3	**Dana**	Oromia	*West Hararge*	8°38'N 40°8'E
31	I4	**Dananley**	Oromia	*East Hararge*	9°38'N 42°51'E
33	F4	**Dangur**	Benishangul Gumuz	*Metekel*	11°22'N 35°57'E
21	H3	**Danse**	Oromia	*Arsi*	8°30'N 40°9'E
28	A5	**Danse**	Oromia	*West Shewa*	9°25'N 38°20'E
18	A2	**Dapo Gumbi**	Oromia	*Ilubabor*	8°54'N 36°5'E
39	F2	**Dara**	Tigray	*Western*	13°19'N 37°15'E
5	J3	**Darar**	Oromia	*Guji*	5°36'N 39°20'E
26	C1	**Darim**	Amhara	*Awi/Agew*	10°44'N 36°35'E
31	H4	**Darimi YeTerara Senselet**	Oromia	*East Hararge*	9°42'N 42°29'E
22	A4	**Daro Lebu YeTerara Senselet**	Oromia	*West Hararge*	8°7'N 40°44'E
21	J5	**Daroti Terara**	Oromia	*West Hararge*	7°58'N 40°35'E
4	D4	**Darrito**	Oromia	*Borena*	5°11'N 38°2'E
4	B1	**Darsi**	SNNPR	*Gamo Gofa*	6°17'N 37°33'E
18	A4	**Darumu**	Oromia	*Ilubabor*	8°21'N 36°7'E
34	D1	**Dauc**	Amhara	*North Gonder*	12°15'N 37°57'E
37	G2	**Daurre**	Afar	*Awsi (Zone 1)*	11°57'N 41°1'E
39	I3	**Debark'**	Amhara	*North Gonder*	13°11'N 37°57'E
20	A3	**Debel Terara**	Oromia	*South West Shewa*	8°48'N 38°28'E
27	I2	**Debet**	Amhara	*East Gojam*	10°29'N 38°1'E
20	E3	**Debocogio**	Amhara	*North Shewa (R3)*	8°45'N 39°18'E
34	D3	**Debra Chente**	Amhara	*South Gonder*	11°31'N 37°55'E
40	B1	**Debra Ghennet**	Tigray	*Central*	13°54'N 38°38'E
39	I2	**Debra Tiun**	Amhara	*North Gonder*	13°22'N 38°4'E
40	C1	**Debre Asa YeTerara Senselet**	Tigray	*Central*	13°44'N 38°58'E
40	E1	**Debre Ma'ir YeTerara Ch'af**	Tigray	*Eastern*	13°53'N 39°23'E
40	E1	**Debre Mar Terara**	Tigray	*Eastern*	13°52'N 39°24'E
35	F2	**Debre Sina**	Amhara	*South Gonder*	11°58'N 38°30'E
27	I5	**Degat'ina Amba**	Oromia	*West Shewa*	9°32'N 37°58'E
26	E3	**Degga**	Oromia	*Horo Guduru*	10°8'N 37°4'E
16	E2	**Deka Jeldesa Terara**	Oromia	*Kelem Wellega*	8°55'N 34°40'E
26	A5	**Delgagala**	Benishangul Gumuz	*Kemashi*	9°27'N 36°6'E
11	G5	**Delle**	SNNPR	*Gamo Gofa*	6°28'N 37°26'E
4	D2	**Delo**	SNNPR	*Segen Peoples'*	5°49'N 37°50'E
37	I4	**Dema'ali Terara**	Afar	*Awsi (Zone 1)*	11°17'N 41°38'E
36	C3	**Dembel**	Amhara	*South Wollo*	11°29'N 40°0'E
22	B1	**Dembi Terara**	Oromia	*West Hararge*	9°21'N 41°4'E
39	F3	**Dendelcau**	Tigray	*Western*	13°17'N 37°13'E
19	H2	**Dendi**	Oromia	*West Shewa*	8°49'N 37°51'E
19	I2	**Dendi Terara**	Oromia	*West Shewa*	8°49'N 38°2'E
31	F5	**Dera Terara**	Dire Dawa	*Dire Dawa*	9°34'N 41°54'E
29	I4	**Derabale Terara**	Afar	*Gabi (Zone 3)*	9°45'N 40°17'E
31	F4	**Dere Meley YeTerara Senselet**	Somali	*Siti*	9°41'N 42°2'E
35	F5	**Deri**	Amhara	*East Gojam*	10°55'N 38°21'E
19	G2	**Derico**	Oromia	*West Shewa*	8°56'N 37°36'E
5	I5	**Derredima**	Oromia	*Borena*	4°53'N 39°11'E
31	H1	**Deryo**	Somali	*Siti*	10°52'N 42°38'E
16	E3	**Dewi Terara**	Oromia	*Kelem Wellega*	8°41'N 34°42'E

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31	H5	**Dibriuein**	Oromia	*East Hararge*	9°35'N 42°33'E
18	C2	**Digga**	Oromia	*East Wellega*	9°2'N 36°29'E
36	C1	**Dighim**	Afar	*Fenti (Zone 4)*	12°14'N 40°10'E
40	D2	**Dilarye Terara**	Tigray	*Central*	13°36'N 39°1'E
25	G3	**Dildessa**	Benishangul Gumuz	*Asosa*	10°15'N 35°8'E
22	B3	**Dimbiba YeTerara Senselet**	Oromia	*West Hararge*	8°40'N 41°2'E
40	D1	**Dira Amba Terara**	Tigray	*Central*	13°39'N 39°2'E
18	D5	**Dire YeTerara Senselet**	Oromia	*East Wellega*	9°18'N 36°48'E
4	B1	**Dita**	SNNPR	*Gamo Gofa*	6°14'N 37°28'E
31	J4	**Djebi Abeyou**	Somali	*Fafan*	9°51'N 42°59'E
22	D1	**Djemi**	Oromia	*East Hararge*	9°21'N 41°34'E
28	D3	**Doba**	Amhara	*North Shewa (R3)*	10°3'N 39°5'E
31	G3	**Doba Terara**	Somali	*Siti*	9°59'N 42°16'E
37	I2	**Dobi YeTerara Senselet**	Afar	*Awsi (Zone 1)*	11°58'N 41°32'E
12	D4	**Doda**	Oromia	*West Arsi*	6°54'N 39°14'E
21	J5	**Dodota Terara**	Oromia	*West Hararge*	7°59'N 40°33'E
21	H5	**Dofen Terara**	Afar	*Gabi (Zone 3)*	9°20'N 40°8'E
11	F5	**Doghe**	SNNPR	*Gamo Gofa*	6°36'N 37°23'E
32	B5	**Dong**	Benishangul Gumuz	*Kemashi*	11°0'N 35°3'E
19	F2	**Dongoro YeTerara Senselet**	Oromia	*West Shewa*	9°8'N 37°15'E
39	G4	**Dredebbe**	Amhara	*North Gonder*	12°42'N 37°35'E
9	G4	**Duco**	SNNPR	*Bench Maji*	6°54'N 35°10'E
41	F5	**Duffat**	Tigray	*Southern*	12°30'N 39°30'E
11	I4	**Duguna**	SNNPR	*Wolayita*	6°57'N 38°3'E
24	D2	**Dul**	Benishangul Gumuz	*Asosa*	10°29'N 34°24'E
31	H4	**Duleti Terara**	Somali	*Siti*	9°44'N 42°28'E
10	D3	**Dulla**	SNNPR	*Kaffa*	7°9'N 36°38'E
25	H2	**Duma**	Benishangul Gumuz	*Metekel*	10°20'N 35°22'E
34	D1	**Dumi**	Amhara	*South Gonder*	12°14'N 37°50'E
22	C1	**Dunk'uk'u Terara**	Oromia	*West Hararge*	9°10'N 41°9'E
31	G1	**Durdur**	Somali	*Siti*	10°52'N 42°16'E
4	J3	**Duro**	SNNPR	*Segen Peoples'*	5°31'N 37°12'E
12	C3	**Duro Terara**	Oromia	*West Arsi*	7°14'N 38°49'E

E

39	G2	**Ecimcia**	Amhara	*North Gonder*	13°19'N 37°25'E
4	C3	**Edulei**	SNNPR	*Segen Peoples'*	5°39'N 37°40'E
19	F4	**Egan**	Oromia	*Jimma*	8°25'N 37°16'E
20	E1	**Egdu**	Amhara	*North Shewa (R3)*	9°17'N 39°18'E
41	F2	**Eghir Eriva**	Tigray	*Southern*	13°28'N 39°40'E
31	G1	**Egle**	Somali	*Siti*	10°46'N 42°18'E
19	J4	**Egu**	SNNPR	*Gurage*	8°22'N 38°11'E
25	G1	**El Danab**	Benishangul Gumuz	*Asosa*	10°41'N 35°4'E
14	D4	**El Uak**	Oromia	*Bale*	6°51'N 41°35'E
41	G3	**Ela Callo**	Afar	*Kilbati (Zone 2)*	13°6'N 40°0'E
31	H3	**Eles-Terara**	Somali	*Siti*	10°12'N 42°36'E
33	G3	**Elfing Bar**	Amhara	*Awi/Agew*	11°47'N 36°15'E
6	A5	**Eluddoro**	Oromia	*Guji*	4°48'N 39°38'E
28	A2	**Embeleti**	Amhara	*East Gojam*	10°37'N 38°25'E
39	J3	**Encetcab**	Amhara	*North Gonder*	13°6'N 38°9'E
38	D4	**Encheddiba**	Amhara	*North Gonder*	12°37'N 36°37'E
25	I3	**Enemo**	Benishangul Gumuz	*Kemashi*	9°57'N 35°46'E
31	I1	**Enlon-Godon**	Somali	*Siti*	10°45'N 42°41'E
31	H1	**Erene**	Somali	*Siti*	10°56'N 42°36'E
20	C2	**Erer Terara**	Oromia	*East Shewa*	8°54'N 38°58'E
39	H4	**Ernambe**	Amhara	*North Gonder*	12°55'N 37°38'E
12	E1	**Erosa**	Oromia	*Arsi*	7°51'N 39°23'E
36	D1	**Ererei**	Afar	*Fenti (Zone 4)*	12°9'N 40°19'E
24	E3	**Eruoldi**	Benishangul Gumuz	*Asosa*	10°13'N 34°37'E
39	G1	**Eto**	Tigray	*Western*	13°40'N 37°23'E
35	I2	**Ezeran**	Amhara	*North Wollo*	12°1'N 39°11'E
34	D2	**Ezub**	Amhara	*South Gonder*	12°6'N 37°48'E
25	G2	**Fado**	Benishangul Gumuz	*Kemashi*	10°29'N 35°7'E

F

32	B5	**Fadokha**	Benishangul Gumuz	*Kemashi*	10°57'N 34°58'E
25	G3	**Fagaddo**	Benishangul Gumuz	*Asosa*	10°11'N 35°9'E
21	F4	**Fagogi**	Oromia	*Arsi*	8°18'N 39°39'E
19	I2	**Faicha**	Oromia	*West Shewa*	8°56'N 38°0'E
23	F2	**Falti**	Oromia	*East Hararge*	9°2'N 41°54'E
24	D3	**Famoghe**	Benishangul Gumuz	*Asosa*	10°15'N 34°24'E
25	F3	**Farboghi**	Benishangul Gumuz	*Asosa*	10°9'N 34°47'E
25	G3	**Fari**	Benishangul Gumuz	*Asosa*	10°15'N 35°7'E
30	A5	**Farsis**	Afar	*Gabi (Zone 3)*	9°27'N 40°41'E
3	I3	**Fascalli**	SNNPR	*South Omo*	5°30'N 36°46'E
22	E1	**Fedni Terara**	Oromia	*East Hararge*	9°9'N 41°48'E
19	F4	**Fego**	Oromia	*Jimma*	8°9'N 37°12'E
40	E3	**Felege Hafo Terara**	Tigray	*Southern*	13°16'N 39°21'E
21	G2	**Fentale Isate Gemora**	Oromia	*East Shewa*	8°59'N 39°56'E
39	I3	**Feraca**	Amhara	*North Gonder*	13°12'N 37°54'E
31	I2	**Feras**	Somali	*Siti*	10°27'N 42°48'E
23	G4	**Fik'**	Somali	*Nogob*	8°7'N 42°18'E
12	E2	**Filfo Terara**	Oromia	*Arsi*	7°22'N 39°21'E
40	E3	**Fingalat**	Tigray	*Southern*	13°9'N 39°23'E
20	B1	**Fota Terara**	Oromia	*West Shewa*	9°13'N 38°30'E
33	I5	**Fudi**	Amhara	*Awi/Agew*	10°55'N 36°47'E
17	I5	**Fugu**	Oromia	*Ilubabor*	8°3'N 35°33'E
33	H1	**Fuldana**	Amhara	*North Gonder*	12°10'N 36°28'E
5	I4	**Fulu**	Oromia	*Guji*	5°8'N 39°12'E
31	H5	**Funyan Ch'ali Terara**	Oromia	*East Hararge*	9°24'N 42°30'E
31	H5	**Funyan Jufu Terara**	Oromia	*East Hararge*	9°24'N 42°26'E
36	C3	**Fura**	Afar	*Awsi (Zone 1)*	11°44'N 40°4'E
22	B4	**Furdo Terara**	Oromia	*West Hararge*	8°11'N 40°55'E

G

38	D2	**Gababu**	Tigray	*Western*	13°27'N 36°45'E
18	E4	**Gabana**	Oromia	*Jimma*	8°8'N 36°53'E
37	H5	**Gabillema**	Afar	*Awsi (Zone 1)*	11°5'N 41°16'E
33	H2	**Gabina**	Amhara	*Awi/Agew*	11°58'N 36°26'E
41	H1	**Gabuli**	Afar	*Kilbati (Zone 2)*	13°40'N 40°16'E
4	B2	**Gacio**	SNNPR	*Gamo Gofa*	6°9'N 37°32'E
37	G1	**Gaddaclo**	Afar	*Awsi (Zone 1)*	12°13'N 40°59'E
2	C2	**Gafala**	SNNPR	*Bench Maji*	6°6'N 35°22'E
39	G4	**Gai**	Amhara	*North Gonder*	12°42'N 37°29'E
8	E4	**Gak**	Gambella	*Agnuak*	6°51'N 34°38'E
37	I2	**Gala**	Afar	*Awsi (Zone 1)*	11°51'N 41°41'E
21	F2	**Gala Terara**	Amhara	*North Shewa (R3)*	8°50'N 39°32'E
9	I4	**Galajiba**	SNNPR	*Bench Maji*	6°45'N 35°39'E
29	J4	**Galalu**	Afar	*Gabi (Zone 3)*	9°47'N 40°38'E
12	E2	**Galama**	Oromia	*Arsi*	7°39'N 39°22'E
37	G4	**Galatu**	Afar	*Awsi (Zone 1)*	11°17'N 41°6'E
38	C5	**Galea**	Amhara	*North Gonder*	12°25'N 36°26'E
36	D1	**Galicoma**	Afar	*Fenti (Zone 4)*	12°12'N 40°15'E
36	D1	**Gamabolu**	Afar	*Fenti (Zone 4)*	12°21'N 40°15'E
11	H2	**Gambata**	SNNPR	*Kembata Tembaro*	7°20'N 37°50'E
36	C2	**Gambato**	Afar	*Fenti (Zone 4)*	11°51'N 40°3'E
4	E2	**Gamso**	SNNPR	*Gedio*	6°3'N 38°8'E
35	H2	**Gana**	Amhara	*North Wollo*	12°1'N 38°52'E
38	C4	**Gandeba**	Amhara	*North Gonder*	12°41'N 36°23'E
33	I2	**Gandi**	Amhara	*North Gonder*	11°58'N 36°48'E
30	D4	**Gara Adi Terara**	Somali	*Siti*	9°46'N 41°34'E
12	C1	**Gara Alutu**	Oromia	*Arsi*	7°46'N 38°47'E
31	H5	**Gara Amola**	Oromia	*East Hararge*	9°33'N 42°30'E
14	D2	**Gara Colba**	Oromia	*Bale*	7°28'N 41°22'E
20	B2	**Gara Furi Terara**	Oromia	*South West Shewa*	8°53'N 38°41'E
31	I4	**Gara Garri**	Somali	*Fafan*	9°43'N 42°50'E
31	I5	**Gara Goreis**	Oromia	*East Hararge*	9°28'N 42°38'E
28	B4	**Gara Guda Terara**	Oromia	*North Shewa (R4)*	9°47'N 38°38'E
22	B2	**Gara K'ufa**	Oromia	*West Hararge*	9°8'N 41°5'E
22	E1	**Gara Muleta**	Oromia	*East Hararge*	9°15'N 41°44'E
25	I4	**Gara Nasa**	Benishangul Gumuz	*Kemashi*	9°42'N 35°33'E
12	E2	**Gara Sero**	Oromia	*Arsi*	7°36'N 39°22'E
23	G5	**Gara-Fik-Uen**	Somali	*Nogob*	8°4'N 42°20'E
41	F3	**Garagiam**	Tigray	*Southern*	13°6'N 39°37'E
26	D4	**Garamate**	Oromia	*East Wellega*	9°44'N 36°39'E
12	B4	**Garamba**	SNNPR	*Sidama*	6°44'N 38°39'E

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33	H2	**Garasgh**	Amhara	*North Gonder*	12°0'N 36°39'E
38	C2	**Garasitu**	Amhara	*North Gonder*	13°20'N 36°28'E
41	I2	**Garbena**	Afar	*Kilbati* (*Zone 2*)	13°27'N 40°24'E
36	C5	**Garfa**	Amhara	*Oromia*	11°5'N 40°1'E
11	F2	**Garo**	Oromia	*Jimma*	7°25'N 37°17'E
36	B1	**Garra Aleucia**	Amhara	*North Wollo*	12°9'N 39°41'E
18	D5	**Garugge**	Oromia	*Jimma*	8°2'N 36°52'E
41	I4	**Garule**	Afar	*Kilbati* (*Zone 2*)	12°55'N 40°17'E
35	J2	**Gaso**	Amhara	*North Wollo*	11°50'N 39°21'E
10	B1	**Gaua**	Oromia	*Jimma*	7°39'N 36°8'E
35	H1	**Gavsigivla**	Amhara	*Wag Himra*	12°21'N 39°4'E
33	H1	**Gaz Gimb**	Amhara	*North Gonder*	12°9'N 36°35'E
24	D3	**Gaza**	Benishangul Gumuz	*Asosa*	10°5'N 34°22'E
40	B1	**Gebaco**	Tigray	*Central*	13°49'N 38°38'E
23	I4	**Gebel Goreis**	Oromia	*East Hararge*	8°26'N 42°39'E
38	E2	**Gebre Harya Terara**	Tigray	*Western*	13°26'N 37°2'E
39	F2	**Gebre Harya Terara**	Tigray	*Western*	13°20'N 37°12'E
11	I4	**Gedano**	SNNPR	*Sidama*	6°38'N 38°8'E
37	G1	**Ged'elu Terara**	Afar	*Awsi* (*Zone 1*)	12°24'N 41°4'E
22	B5	**Gedera Terara**	Oromia	*West Hararge*	8°4'N 40°55'E
26	B5	**Gello**	Benishangul Gumuz	*Kemashi*	9°33'N 36°12'E
11	F4	**Genet**	SNNPR	*Dawro*	6°45'N 37°11'E
36	D3	**Gengoyta Terara**	Afar	*Awsi* (*Zone 1*)	11°41'N 40°21'E
4	B2	**Genta Terara**	SNNPR	*Gamo Gofa*	6°4'N 37°27'E
40	D5	**Gerbaco**	Amhara	*Wag Himra*	12°26'N 39°5'E
20	C3	**Gerbicha Terara**	Oromia	*East Shewa*	8°41'N 38°57'E
40	C3	**Gerum**	Tigray	*Central*	13°16'N 38°57'E
20	A4	**Gesh Megal Terara**	Oromia	*South West Shewa*	8°24'N 38°24'E
9	J1	**Gesha**	SNNPR	*Kaffa*	7°44'N 35°52'E
23	F2	**Geyle Terara**	Oromia	*East Hararge*	9°3'N 41°52'E
39	F1	**Geza Agel**	Tigray	*Western*	13°56'N 37°7'E
38	D2	**Ghecciau**	Amhara	*North Gonder*	13°22'N 36°49'E
36	B1	**Ghedaro**	Afar	*Fenti* (*Zone 4*)	12°12'N 39°49'E
40	J4	**Ghedeon**	Amhara	*North Gonder*	12°38'N 38°23'E
39	G4	**Ghedi**	Amhara	*North Gonder*	12°39'N 37°31'E
14	D4	**Ghelbi**	Oromia	*Bale*	6°47'N 41°27'E
17	J5	**Ghermana**	Oromia	*Jimma*	7°54'N 35°56'E
4	E2	**Ghibigia**	Oromia	*Borena*	6°2'N 38°5'E
37	I3	**Ghifa**	Afar	*Awsi* (*Zone 1*)	11°37'N 41°40'E
41	H4	**Ghimmeri**	Afar	*Kilbati* (*Zone 2*)	12°56'N 40°12'E
14	E5	**Giabis**	Somali	*Afder*	6°23'N 41°36'E
40	D5	**Giala**	Amhara	*Wag Himra*	12°24'N 39°4'E
11	G1	**Giangero**	SNNPR	*Yem*	7°45'N 37°28'E
39	H3	**Gianora**	Amhara	*North Gonder*	13°2'N 37°37'E
18	E1	**Giaue**	Oromia	*West Shewa*	9°9'N 37°3'E
26	B4	**Gibir**	Benishangul Gumuz	*Kemashi*	9°44'N 36°8'E
22	E2	**Gicha Terara**	Oromia	*East Hararge*	8°51'N 41°51'E
26	E3	**Gidda**	Oromia	*East Wellega*	10°0'N 36°52'E
33	G2	**Gilfu**	Amhara	*North Gonder*	12°6'N 36°12'E
34	C3	**Gina**	Amhara	*South Gonder*	11°35'N 37°41'E
15	H3	**Giogo**	Somali	*Nogob*	7°10'N 42°35'E
13	H4	**Goba**	Oromia	*Bale*	6°55'N 40°10'E
31	G3	**Goba-Dzher**	Somali	*Siti*	10°1'N 42°12'E
31	H5	**Gobbi Hamer**	Oromia	*East Hararge*	9°24'N 42°34'E
30	E2	**Gobe'a Terara**	Somali	*Siti*	10°29'N 41°44'E
3	I2	**Goda**	SNNPR	*South Omo*	5°50'N 36°54'E
10	A3	**Goda**	SNNPR	*Kaffa*	7°10'N 36°5'E
31	I1	**Godire**	Somali	*Siti*	10°56'N 42°50'E
13	H2	**Gogiabe**	Oromia	*Arsi*	7°30'N 40°5'E
15	G4	**Goja Terara**	Somali	*Shabelle*	6°46'N 42°9'E
12	A2	**Golgio**	SNNPR	*Alaba*	7°32'N 38°21'E
38	E2	**Golgoda**	Amhara	*North Gonder*	13°19'N 37°1'E
26	D4	**Gomboch'Terara**	Oromia	*East Wellega*	9°45'N 36°43'E
39	G3	**Gombolo**	Amhara	*North Gonder*	13°11'N 37°22'E
36	J5	**Gomoyta YeTerara Senselet**	Afar	*Fenti* (*Zone 4*)	12°18'N 40°32'E
26	C4	**Gondor Terara**	Oromia	*East Wellega*	9°53'N 36°33'E
33	H5	**Gongi**	Amhara	*Awi/Agew*	10°58'N 36°38'E
18	C2	**Gonjo**	Oromia	*East Wellega*	9°2'N 36°23'E
9	H4	**Gorei**	SNNPR	*Bench Maji*	6°38'N 35°27'E
20	C1	**Gorfo Terara**	Oromia	*North Shewa* (*R4*)	9°15'N 38°52'E
10	A1	**Gorgota**	Oromia	*Jimma*	7°45'N 36°6'E
26	E5	**Goroch'an**	Oromia	*Horo Guduru*	9°26'N 37°4'E
22	E3	**Gorogarbi**	Oromia	*East Hararge*	8°41'N 41°48'E
23	F3	**Gorru**	Oromia	*East Hararge*	8°33'N 42°4'E
12	C4	**Gorte Terara**	Oromia	*West Arsi*	6°50'N 38°50'E
26	E4	**Gorte Terara**	Oromia	*Horo Guduru*	9°38'N 36°56'E
18	B1	**Gotto Muri**	Benishangul Gumuz	*Kemashi*	9°12'N 36°10'E
40	E3	**Gowdi Hayrat Terara**	Tigray	*Southern*	13°7'N 39°26'E
10	B3	**Guba**	SNNPR	*Kaffa*	7°11'N 36°10'E
36	A4	**Guba YeTerara Senselet**	Amhara	*South Wollo*	11°12'N 39°37'E
4	D4	**Gubba**	Oromia	*Borena*	5°25'N 37°58'E
26	C2	**Gubbi**	Benishangul Gumuz	*Kemashi*	10°19'N 36°36'E
25	I2	**Guciar**	Benishangul Gumuz	*Metekel*	10°29'N 35°38'E
20	E2	**Guga**	Amhara	*North Shewa* (*R3*)	9°3'N 39°26'E
4	B1	**Guge**	SNNPR	*Gamo Gofa*	6°12'N 37°30'E
21	G4	**Gugu**	Oromia	*Arsi*	8°12'N 39°58'E
21	G4	**Gugu**	Oromia	*Arsi*	8°15'N 39°55'E
3	G3	**Guista**	SNNPR	*South Omo*	5°38'N 36°28'E
20	C3	**Guji Terara**	Oromia	*East Shewa*	8°47'N 38°50'E
24	E2	**Gule**	Benishangul Gumuz	*Asosa*	10°30'N 34°31'E
22	B1	**Gulube Terara**	Oromia	*West Hararge*	9°19'N 40°55'E
26	C2	**Gum**	Amhara	*Awi/Agew*	10°36'N 36°35'E
17	G4	**Guma**	Oromia	*Ilubabor*	8°17'N 35°2'E
17	G2	**Guma Guda YeTerara Ch'af**	Oromia	*Kelem Wellega*	9°1'N 35°7'E
39	G1	**Gumai Daro**	Tigray	*Western*	13°45'N 37°28'E
31	H1	**Gumar**	Somali	*Siti*	10°56'N 42°27'E
41	F4	**Gumasir**	Tigray	*Southern*	12°56'N 39°44'E
21	H2	**Gumbi**	Oromia	*West Hararge*	8°58'N 40°13'E
38	D4	**Gumenta**	Amhara	*North Gonder*	12°54'N 36°38'E
36	D1	**Gummeli**	Afar	*Fenti* (*Zone 4*)	12°12'N 40°24'E
34	E3	**Guna Terara**	Amhara	*South Gonder*	11°43'N 38°14'E
29	F4	**Gundi**	Amhara	*North Shewa* (*R3*)	9°46'N 39°43'E
4	B5	**Gundile**	Oromia	*Borena*	4°54'N 37°24'E
21	H4	**Gura Terara**	Oromia	*Arsi*	8°8'N 40°13'E
36	D3	**Gura'ale Terara**	Afar	*Awsi* (*Zone 1*)	11°40'N 40°25'E
17	H4	**Guraccio**	Oromia	*Ilubabor*	8°26'N 35°20'E
9	F4	**Guraferda YeTerara Senselet**	SNNPR	*Bench Maji*	6°55'N 34°59'E
20	A4	**Gurage**	Oromia	*South West Shewa*	8°24'N 38°24'E
9	I4	**Gurboji**	SNNPR	*Bench Maji*	6°41'N 35°43'E
9	J2	**Gurguri**	SNNPR	*Kaffa*	7°21'N 35°54'E
9	H3	**Gurma**	SNNPR	*Bench Maji*	6°58'N 35°18'E
4	A3	**Guroza Terara**	SNNPR	*Segen Peoples'*	5°35'N 37°17'E
18	E1	**Gushis YeTerara Ch'af**	Oromia	*East Wellega*	9°18'N 36°57'E
19	H3	**Guto**	Oromia	*South West Shewa*	8°43'N 37°45'E
26	C2	**Gutr**	Amhara	*West Gojam*	10°30'N 36°35'E
29	G2	**Gwasa Terara**	Amhara	*North Shewa* (*R3*)	10°25'N 39°53'E

H

13	I4	**Habrona Terara**	Oromia	*Bale*	6°41'N 40°27'E
7	I2	**Hada Kumbi**	Somali	*Afder*	5°58'N 41°39'E
41	F3	**Hadele Terara**	Tigray	*Southern*	13°8'N 39°41'E
41	F4	**Haia Olel**	Tigray	*Southern*	12°43'N 39°44'E
41	J4	**Halaite**	Afar	*Fenti* (*Zone 4*)	12°37'N 40°34'E
37	G4	**Hallu**	Afar	*Awsi* (*Zone 1*)	11°23'N 41°9'E
31	G5	**Hama YeTerara Senselet**	Oromia	*East Hararge*	9°32'N 42°10'E
36	C3	**Hamarko Terara**	Amhara	*South Wollo*	11°36'N 39°58'E
26	D5	**Hambule Terara**	Oromia	*East Wellega*	9°28'N 36°50'E
19	I3	**Hamdo**	Oromia	*West Shewa*	8°48'N 37°54'E
36	A5	**Hara YeTerara Senselet**	Amhara	*South Wollo*	11°4'N 39°36'E
37	F1	**Hararu Terara**	Afar	*Awsi* (*Zone 1*)	12°10'N 40°49'E
21	F3	**Harbona Terara**	Oromia	*East Shewa*	8°42'N 39°35'E
39	G3	**Haria**	Amhara	*North Gonder*	13°3'N 37°31'E
31	G2	**Harr**	Somali	*Siti*	10°28'N 42°18'E
39	I2	**Haweza Terara**	Amhara	*North Gonder*	13°25'N 38°4'E
40	B2	**Hay**	Amhara	*North Gonder*	13°21'N 38°31'E
37	I4	**Haytankoma Terara**	Afar	*Awsi* (*Zone 1*)	11°21'N 41°35'E

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39	F1	**Hemberti**	Tigray	*Western*	13°55'N 37°9'E
23	H1	**Herreder**	Oromia	*East Hararge*	9°10'N 42°23'E
18	D4	**Hesa**	Oromia	*Ilubabor*	8°14'N 36°41'E
36	A1	**Hobat**	Amhara	*North Wollo*	12°12'N 39°34'E
37	F1	**Hodale Terara**	Afar	*Awsi (Zone 1)*	12°21'N 40°44'E
7	J2	**Hogdu**	Somali	*Afder*	6°6'N 41°51'E
19	F4	**Hola**	Oromia	*Jimma*	8°16'N 37°15'E
12	B4	**Holo Terara**	SNNPR	*Sidama*	6°44'N 38°34'E
12	B5	**Honku**	SNNPR	*Sidama*	6°27'N 38°33'E
13	G3	**Hora YeTerara Senselet**	Oromia	*Bale*	7°15'N 39°45'E
31	H1	**Huglo**	Somali	*Siti*	10°44'N 42°23'E
25	J2	**Huladura Terara**	Benishangul Gumuz	*Metekel*	10°18'N 35°49'E
3	H5	**Humu YeTerara Senselet**	SNNPR	*South Omo*	5°0'N 36°40'E
36	D4	**Hurmat Terara**	Afar	*Awsi (Zone 1)*	11°24'N 40°13'E

I

25	H3	**Iagada**	Benishangul Gumuz	*Metekel*	10°17'N 35°22'E
37	J3	**Iaghar**	Afar	*Awsi (Zone 1)*	11°47'N 41°44'E
25	H2	**Iagona**	Benishangul Gumuz	*Metekel*	10°33'N 35°21'E
26	C3	**Ibantu**	Oromia	*East Wellega*	10°10'N 36°25'E
29	F1	**Ieciuol**	Amhara	*South Wollo*	10°50'N 39°30'E
12	D4	**Ilale Terara**	Oromia	*West Arsi*	6°48'N 39°9'E
21	G3	**Ilko Terara**	Oromia	*Arsi*	8°32'N 39°45'E
41	I3	**Imba**	Afar	*Kilbati (Zone 2)*	13°16'N 40°27'E
40	D2	**Imba Shihak'Terara**	Tigray	*Southern*	13°19'N 39°13'E
40	E3	**Imba Ts'emba Terara**	Tigray	*Southern*	13°2'N 39°18'E
40	E2	**Imba Zerfent Korebta**	Tigray	*Central*	13°38'N 39°16'E
41	F1	**Inda Maryam**	Tigray	*Eastern*	13°55'N 39°35'E
36	B5	**Indode Terara**	Amhara	*South Wollo*	10°60'N 39°54'E
27	H1	**Ingia**	Amhara	*East Gojam*	10°42'N 37°42'E
31	G5	**Ink'uftu YeTerara Senselet**	Oromia	*East Hararge*	9°33'N 42°14'E
20	C2	**Int'ot'o Terara**	Addis Ababa	*Region 14*	9°4'N 38°48'E
35	I5	**Ioll**	Amhara	*South Wollo*	11°1'N 39°6'E
25	H3	**Ionghi**	Benishangul Gumuz	*Kemashi*	10°1'N 35°21'E
35	I1	**Israel Amba**	Amhara	*Wag Himra*	12°16'N 39°6'E

J

2	C1	**Jaba**	SNNPR	*Bench Maji*	6°15'N 35°14'E
38	B2	**Jabal Abu Takia**	Amhara	*North Gonder*	13°18'N 36°18'E
25	A5	**Jabal Belangashe**	Benishangul Gumuz	*Asosa*	10°48'N 34°52'E
32	B5	**Jabal Belesagado**	Benishangul Gumuz	*Asosa*	10°52'N 34°57'E
24	D1	**Jabal Gamendu**	Benishangul Gumuz	*Asosa*	10°41'N 34°24'E
24	E1	**Jabal Kashangaro**	Benishangul Gumuz	*Asosa*	10°54'N 34°36'E
24	C5	**Jabal Manga**	Benishangul Gumuz	*Asosa*	9°33'N 34°6'E
38	B4	**Jabal Maqbarah**	Amhara	*North Gonder*	12°41'N 36°11'E
2	B3	**Jabal Tomadur**	SNNPR	*Bench Maji*	5°38'N 35°8'E
24	C4	**Jabal Zazing**	Benishangul Gumuz	*Asosa*	9°35'N 34°10'E
33	F2	**Jagaighi Tarara**	Amhara	*Awi/Agew*	11°52'N 36°8'E
33	H2	**Jamifala**	Amhara	*North Gonder*	12°7'N 36°26'E
24	D4	**Jebel Bange**	Benishangul Gumuz	*Asosa*	9°43'N 34°18'E
38	B4	**Jebel Dalasa**	Amhara	*North Gonder*	12°54'N 36°11'E
24	C5	**Jebel Dubu**	Benishangul Gumuz	*Asosa*	9°25'N 34°7'E
24	D4	**Jebel Gogot**	Benishangul Gumuz	*Asosa*	9°55'N 34°15'E
24	D5	**Jebel Kasr**	Benishangul Gumuz	*Asosa*	9°25'N 34°16'E
16	D1	**Jebel Shomala**	Benishangul Gumuz	*Asosa*	9°15'N 34°26'E
33	F2	**Jebel Umm Zenegia**	Amhara	*North Gonder*	12°6'N 35°59'E
33	F1	**Jebel Umm Zenidi**	Amhara	*North Gonder*	12°15'N 35°57'E
26	A4	**Jeldesa**	Benishangul Gumuz	*Kemashi*	9°39'N 36°1'E
26	D4	**Jeldu Terara**	Oromia	*Horo Guduru*	9°39'N 36°51'E
22	B2	**Jelo Terara**	Oromia	*West Hararge*	9°0'N 40°51'E
31	G5	**Jewer YeTerara Senselet**	Oromia	*East Hararge*	9°24'N 42°11'E
19	G3	**Jibat**	Oromia	*West Shewa*	8°47'N 37°28'E
39	H4	**Jibo Terara**	Amhara	*North Gonder*	12°46'N 37°41'E
18	C2	**Jimata**	Oromia	*East Wellega*	9°7'N 36°23'E
19	I2	**Jirma**	Oromia	*West Shewa*	9°5'N 38°0'E

K

9	I3	**Kaka Terara**	SNNPR	*Bench Maji*	6°58'N 35°39'E
7	J3	**Kalech**	Somali	*Afder*	5°40'N 41°50'E
9	G4	**Kamtis**	SNNPR	*Bench Maji*	6°47'N 35°7'E
29	G2	**Kebroy Maryam Terara**	Amhara	*North Shewa (R3)*	10°27'N 39°54'E
12	D2	**K'ech'a Terara**	Oromia	*Arsi*	7°22'N 39°9'E
20	A4	**K'ech'a Terara**	Oromia	*South West Shewa*	8°18'N 38°23'E
18	D1	**Kedo YeTerara Ch'af**	Oromia	*East Wellega*	9°12'N 36°42'E
21	J2	**Kentari Terara**	Oromia	*West Hararge*	8°54'N 40°35'E
20	C2	**Kereyu Terara**	Oromia	*East Shewa*	8°53'N 38°58'E
40	D1	**K'ernale Terara**	Tigray	*Central*	13°42'N 39°4'E
31	G4	**Kerora YeTerara Senselet**	Oromia	*East Hararge*	9°39'N 42°15'E
31	G5	**K'ilisa Terara**	Oromia	*East Hararge*	9°28'N 42°13'E
39	J3	**Kidis Yared**	Amhara	*North Gonder*	13°18'N 38°20'E
39	G3	**Kirakir**	Amhara	*North Gonder*	13°15'N 37°25'E
14	E2	**Koloto**	Oromia	*Bale*	7°27'N 41°49'E
26	C5	**Koma Terara**	Benishangul Gumuz	*Kemashi*	9°29'N 36°25'E
18	C2	**Komto Terara**	Oromia	*East Wellega*	9°8'N 36°37'E
21	F2	**Kora**	Amhara	*North Shewa (R3)*	8°50'N 39°39'E
21	J5	**Korbelli**	Somali	*Siti*	10°56'N 41°56'E
12	D4	**Korduro Terara**	Oromia	*West Arsi*	6°50'N 39°9'E
13	I2	**K'ori YeTerara Ch'af**	Oromia	*Bale*	7°31'N 40°17'E
12	D5	**K'ork'ite YeTerara Senselet**	SNNPR	*Sidama*	6°25'N 39°0'E
40	D1	**Koro Terara**	Tigray	*Central*	13°42'N 39°5'E
35	J3	**Koso Amba**	Amhara	*North Wollo*	11°46'N 39°26'E
11	F4	**Koysha Terara**	SNNPR	*Dawro*	6°50'N 37°15'E
12	D2	**K'ubsa Terara**	Oromia	*Arsi*	7°25'N 38°59'E
9	G4	**Kuda**	SNNPR	*Bench Maji*	6°47'N 35°12'E
2	C2	**Kulbisa**	SNNPR	*Bench Maji*	6°4'N 35°18'E
30	E5	**K'ulubi**	Somali	*Siti*	9°29'N 41°42'E
6	A1	**Kundu**	Oromia	*Bale*	6°23'N 39°35'E
31	G5	**K'undudo Terara**	Oromia	*East Hararge*	9°26'N 42°21'E
2	B2	**Kungul**	SNNPR	*Bench Maji*	5°54'N 34°60'E
29	I4	**Kurbe Terara**	Afar	*Gabi (Zone 3)*	9°53'N 40°26'E
2	C2	**Kurma**	SNNPR	*Bench Maji*	6°1'N 35°27'E
37	H2	**Kurub Terara**	Afar	*Awsi (Zone 1)*	11°53'N 41°13'E
15	H4	**Kus Dulamo YeTerara Senselet**	Somali	*Shabelle*	6°50'N 42°32'E
27	H5	**Kusaye Terara**	Oromia	*West Shewa*	9°24'N 37°48'E
2	B2	**Kutul**	SNNPR	*Bench Maji*	5°54'N 35°2'E
2	B2	**Kutul Birino**	SNNPR	*Bench Maji*	5°54'N 35°1'E
21	F2	**Kuyu Terara**	Amhara	*North Shewa (R3)*	8°53'N 39°39'E
35	I3	**K'want'e Terara**	Amhara	*North Wollo*	11°39'N 39°18'E

L

18	C1	**Laca**	Oromia	*East Wellega*	9°17'N 36°36'E
26	D5	**Lafto Terara**	Oromia	*Horo Guduru*	9°34'N 36°51'E
13	F3	**Lajo**	Oromia	*West Arsi*	7°12'N 39°38'E
31	F5	**Lalu Terara**	Dire Dawa	*Dire Dawa*	9°34'N 42°5'E
30	B2	**Langudi**	Afar	*Gabi (Zone 3)*	10°37'N 41°2'E
34	B5	**Lechema**	Amhara	*West Gojam*	10°57'N 37°17'E
36	B4	**Legda**	Amhara	*South Wollo*	11°23'N 39°54'E
25	H4	**Lein**	Benishangul Gumuz	*Kemashi*	9°47'N 35°27'E
14	D4	**Lele**	Oromia	*Bale*	6°42'N 41°27'E
26	C3	**Lench'a Terara**	Oromia	*East Wellega*	9°57'N 36°34'E
34	B5	**Lich'ma**	Amhara	*West Gojam*	10°57'N 37°17'E
34	B4	**Lieu**	Amhara	*West Gojam*	11°9'N 37°19'E
40	B3	**Liga**	Amhara	*Wag Himra*	13°16'N 38°36'E
34	B4	**Lijambera**	Amhara	*West Gojam*	11°7'N 37°24'E
41	H4	**Limmo**	Afar	*Fenti (Zone 4)*	12°50'N 40°12'E
40	D3	**Lisha**	Tigray	*Southern*	13°13'N 39°6'E
21	I3	**Lochu**	Oromia	*West Hararge*	8°41'N 40°19'E
37	F2	**Loma Terara**	Afar	*Awsi (Zone 1)*	11°57'N 40°55'E
21	I3	**Lucio**	Oromia	*West Hararge*	8°44'N 40°22'E
33	G1	**Luza**	Amhara	*North Gonder*	12°11'N 36°20'E

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M

39	G3	**Macatat**	Amhara	*North Gonder*	13°10'N 37°31'E
35	I2	**Machel Geras**	Amhara	*North Wollo*	12°6'N 39°19'E
23	I3	**Macoda**	Oromia	*East Hararge*	8°42'N 42°44'E
18	A3	**Madugga**	Oromia	*Ilubabor*	8°36'N 36°5'E
40	E1	**Magab**	Tigray	*Eastern*	13°52'N 39°18'E
41	H4	**Magalle**	Afar	*Kilbati (Zone 2)*	12°53'N 40°3'E
36	C4	**Maghenta**	Afar	*Awsi (Zone 1)*	11°15'N 40°10'E
41	H3	**Mahalta**	Afar	*Kilbati (Zone 2)*	13°1'N 40°13'E
11	F2	**Mai Gudo**	Oromia	*Jimma*	7°29'N 37°12'E
40	E1	**Maiu**	Tigray	*Central*	13°43'N 39°17'E
2	D1	**Maji**	SNNPR	*Bench Maji*	6°9'N 35°36'E
18	C4	**Mamme**	Oromia	*Ilubabor*	8°8'N 36°28'E
32	B4	**Manchelung**	Benishangul Gumuz	*Metekel*	11°25'N 35°5'E
37	G2	**Manda YeTerara Senselet**	Afar	*Awsi (Zone 1)*	11°52'N 41°1'E
19	G5	**Manetti**	Oromia	*Jimma*	8°6'N 37°32'E
29	G3	**Manya YeTerara Senselet**	Afar	*Hari (Zone 5)*	10°4'N 39°56'E
33	I3	**Mara**	Amhara	*West Gojam*	11°29'N 36°49'E
18	A1	**Marecce**	Oromia	*West Wellega*	9°11'N 36°2'E
31	I2	**Marmar Gedle**	Somali	*Siti*	10°30'N 42°45'E
31	G1	**Maror**	Somali	*Siti*	10°53'N 42°17'E
40	D5	**Mascalo**	Amhara	*Wag Himra*	12°32'N 39°1'E
32	E5	**Masinier**	Benishangul Gumuz	*Metekel*	11°5'N 35°48'E
12	B4	**Maskulli**	SNNPR	*Sidama*	6°37'N 38°33'E
20	E2	**Masno**	Amhara	*North Shewa (R3)*	9°8'N 39°24'E
40	E1	**Masobu**	Tigray	*Eastern*	13°49'N 39°28'E
17	F3	**Mawo Terara**	Oromia	*Kelem Wellega*	8°34'N 34°48'E
40	E1	**Mayou**	Tigray	*Eastern*	13°51'N 39°28'E
35	I2	**Mechena**	Amhara	*North Wollo*	11°58'N 39°5'E
34	E5	**Medeg**	Amhara	*East Gojam*	10°56'N 38°16'E
37	G3	**Megenta YeTerara Senselet**	Afar	*Awsi (Zone 1)*	11°28'N 41°11'E
21	F1	**Megezez**	Amhara	*North Shewa (R3)*	9°17'N 39°32'E
39	F3	**Megmna**	Amhara	*North Gonder*	13°4'N 37°10'E
34	B4	**Mekari**	Amhara	*West Gojam*	11°25'N 37°22'E
27	H2	**Mekera Kir Terara**	Amhara	*East Gojam*	10°38'N 37°46'E
31	I1	**Mekho**	Somali	*Siti*	10°48'N 42°40'E
18	A3	**Meko**	Oromia	*Ilubabor*	8°38'N 36°5'E
39	G1	**Melau**	Tigray	*Western*	13°39'N 37°25'E
34	E2	**Melza**	Amhara	*South Gonder*	12°1'N 38°12'E
29	G4	**Membret**	Amhara	*North Shewa (R3)*	9°41'N 39°48'E
37	F1	**Menda Terara**	Afar	*Fenti (Zone 4)*	12°16'N 40°42'E
13	F4	**Mendebo**	Oromia	*West Arsi*	6°50'N 39°40'E
27	I2	**Mengistiwo**	Amhara	*East Gojam*	10°35'N 38°5'E
32	B4	**Mengolf**	Benishangul Gumuz	*Metekel*	11°21'N 35°5'E
38	E5	**Meniuax**	Amhara	*North Gonder*	12°29'N 36°57'E
4	D3	**Mergele Terara**	SNNPR	*Segen Peoples'*	5°42'N 37°50'E
37	H3	**Merkele Terara**	Afar	*Awsi (Zone 1)*	11°31'N 41°15'E
16	E2	**Mero Terara**	Oromia	*Kelem Wellega*	9°0'N 34°45'E
41	F1	**Mesk'el**	Tigray	*Eastern*	13°59'N 39°40'E
39	J5	**Metsefet**	Amhara	*North Gonder*	12°32'N 38°8'E
39	G5	**Mica**	Amhara	*North Gonder*	12°35'N 37°29'E
39	I1	**Mihira'i Sheyt'an Terara**	Tigray	*North Western*	13°56'N 38°6'E
18	E4	**Mile**	Oromia	*Jimma*	8°16'N 36°53'E
31	I2	**Mil'milaki-Terari**	Somali	*Siti*	10°29'N 42°43'E
25	I2	**Mincio**	Benishangul Gumuz	*Metekel*	10°37'N 35°33'E
23	G4	**Mira**	Somali	*Nogob*	8°11'N 42°15'E
40	A5	**Mira**	Amhara	*Wag Himra*	12°29'N 38°28'E
33	I5	**Mirghi**	Amhara	*Awi/Agew*	10°59'N 36°51'E
31	I1	**Mirmir**	Somali	*Siti*	10°50'N 42°51'E
19	F4	**Misciu**	Oromia	*Jimma*	8°11'N 37°17'E
18	E3	**Misingo**	Oromia	*Jimma*	8°28'N 37°2'E
19	F2	**Miti**	Oromia	*West Shewa*	8°58'N 37°22'E
40	D2	**Mits'ah Bered Terara**	Tigray	*Southern*	13°22'N 39°14'E
34	B5	**Mizan**	Amhara	*West Gojam*	11°1'N 37°28'E
34	E3	**Mize**	Amhara	*South Gonder*	11°40'N 38°8'E
31	J5	**Moccanis**	Somali	*Fafan*	9°34'N 42°54'E
23	I3	**Mogor**	Oromia	*East Hararge*	8°34'N 42°50'E
21	I3	**Molticha Terara**	Oromia	*West Hararge*	8°37'N 40°16'E
26	B4	**Morna**	Oromia	*East Wellega*	9°56'N 36°16'E
2	B2	**Mosab Gara**	SNNPR	*Bench Maji*	5°50'N 35°2'E
33	H3	**Mosabia**	Amhara	*Awi/Agew*	11°38'N 36°33'E
41	F2	**Mosobo Terara**	Tigray	*Southern*	13°34'N 39°31'E
18	D2	**Mote Terara**	Oromia	*East Wellega*	9°7'N 36°39'E
36	B4	**Motocolo**	Amhara	*South Wollo*	11°9'N 39°47'E
29	G2	**Mount Abuye Meda**	Amhara	*North Shewa (R3)*	10°33'N 39°48'E
2	C3	**Mount Naita**	SNNPR	*Bench Maji*	5°30'N 35°18'E
20	D4	**Moye Terara**	Oromia	*Arsi*	8°9'N 39°8'E
35	J2	**Muggia**	Amhara	*North Wollo*	12°3'N 39°24'E
11	I1	**Muggo**	SNNPR	*Selti*	7°49'N 37°58'E
2	D2	**Mui**	SNNPR	*Bench Maji*	6°4'N 35°35'E
19	J1	**Mulo**	Oromia	*West Shewa*	9°18'N 38°10'E
26	D4	**Mulu Terara**	Oromia	*East Wellega*	9°43'N 36°44'E
36	D3	**Muoniu**	Afar	*Awsi (Zone 1)*	11°30'N 40°17'E
19	J4	**Mur Terara**	SNNPR	*Gurage*	8°10'N 38°17'E
3	F4	**Murel**	SNNPR	*South Omo*	5°10'N 36°9'E
36	D4	**Murtu**	Afar	*Hari (Zone 5)*	11°14'N 40°15'E
29	J4	**Mutaka**	Afar	*Gabi (Zone 3)*	9°57'N 40°35'E
22	B2	**Mutar YeTerara Senselet**	Oromia	*West Hararge*	9°0'N 40°56'E
28	E3	**Muter**	Amhara	*North Shewa (R3)*	10°3'N 39°16'E
14	D2	**Mutte Mogi**	Oromia	*Bale*	7°24'N 41°33'E

N

39	F3	**Nadir**	Amhara	*North Gonder*	13°3'N 37°19'E
41	F2	**Nahaso**	Tigray	*Eastern*	13°36'N 39°36'E
40	E1	**Nahiso Terara**	Tigray	*Eastern*	13°50'N 39°17'E
2	E5	**Nakua**	SNNPR	*South Omo*	5°6'N 35°53'E
2	B2	**Nebit**	SNNPR	*Bench Maji*	5°59'N 35°6'E
36	B2	**Nedi**	Afar	*Fenti (Zone 4)*	12°6'N 39°55'E
26	C3	**Nefruit**	Oromia	*East Wellega*	10°1'N 36°28'E
16	D3	**Negu**	Oromia	*Kelem Wellega*	8°27'N 34°25'E
40	C3	**Niway YeTerara Senselet**	Tigray	*Central*	13°15'N 38°57'E
9	H4	**Nizan**	SNNPR	*Bench Maji*	6°57'N 35°27'E
40	C1	**Nobit**	Tigray	*Central*	13°42'N 38°45'E
39	H4	**Nora**	Amhara	*North Gonder*	12°43'N 37°41'E
3	F3	**Nyalibong Korebta**	SNNPR	*South Omo*	5°40'N 36°10'E

O

39	H4	**Oaroa**	Amhara	*North Gonder*	12°52'N 37°47'E
24	E2	**Obi**	Benishangul Gumuz	*Asosa*	10°37'N 34°39'E
4	E5	**Obua**	Oromia	*Borena*	4°52'N 38°5'E
16	E3	**Ola**	Oromia	*Kelem Wellega*	8°36'N 34°40'E
38	C3	**Om Zinghir**	Amhara	*North Gonder*	13°3'N 36°25'E
38	B5	**Ombibi**	Amhara	*North Gonder*	12°30'N 36°17'E
30	B5	**Onde**	Somali	*Siti*	9°35'N 41°2'E
7	J2	**Oror**	Somali	*Afder*	6°0'N 41°51'E
37	F2	**Otale Isate Gemora**	Afar	*Awsi (Zone 1)*	12°0'N 40°49'E
10	D3	**Otta**	SNNPR	*Konta*	7°6'N 36°45'E

Q

33	G1	**Quara**	Amhara	*North Gonder*	12°18'N 36°13'E
34	D5	**Quarib**	Amhara	*East Gojam*	11°4'N 37°48'E

R

19	G2	**Rafiso**	Oromia	*West Shewa*	9°0'N 37°30'E
41	H5	**Rair**	Afar	*Fenti (Zone 4)*	12°34'N 40°3'E
40	A3	**Ras Dejen**	Amhara	*North Gonder*	13°14'N 38°22'E
6	B5	**Ridderu**	Somali	*Liben*	4°49'N 39°50'E
21	J5	**Rido Terara**	Oromia	*West Hararge*	8°3'N 40°36'E
18	C3	**Rogghe**	Oromia	*East Wellega*	8°45'N 36°29'E

S

33	I2	**Saba**	Amhara	*North Gonder*	11°50'N 36°44'E
19	F4	**Sacalla**	Oromia	*Jimma*	8°20'N 37°13'E
40	D3	**Sacca**	Tigray	*Southern*	13°0'N 39°6'E
22	C5	**Sacche**	Oromia	*Bale*	8°1'N 41°12'E
35	I4	**Saco**	Amhara	*South Wollo*	11°8'N 39°17'E
21	G3	**Saddeca**	Oromia	*East Shewa*	8°43'N 39°51'E
34	D1	**Safad**	Amhara	*South Gonder*	12°11'N 37°52'E
33	H5	**Sagado**	Amhara	*Awi/Agew*	10°59'N 36°32'E
33	I4	**Saguma**	Amhara	*Awi/Agew*	11°17'N 36°46'E

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37	H5	**Saha Terara**	Afar	*Awsi (Zone 1)*	11°6'N 41°19'E
18	B4	**Saie**	Oromia	*Jimma*	8°8'N 36°10'E
31	G4	**Salala**	Somali	*Siti*	9°50'N 42°13'E
13	F3	**Salmana**	Oromia	*West Arsi*	7°5'N 39°35'E
39	F2	**Sambocce**	Tigray	*Western*	13°19'N 37°11'E
34	D2	**Samo**	Amhara	*South Gonder*	12°7'N 37°57'E
20	C4	**Sap'o Terara**	Oromia	*East Shewa*	8°12'N 38°58'E
39	F5	**Sar**	Amhara	*North Gonder*	12°36'N 37°16'E
34	A5	**Satima**	Amhara	*West Gojam*	10°57'N 37°12'E
19	F1	**Sayul Terara**	Oromia	*Horo Guduru*	9°15'N 37°11'E
40	A3	**Sazza**	Amhara	*North Gonder*	13°16'N 38°26'E
11	H1	**Scerit**	SNNPR	*Hadiya*	7°46'N 37°47'E
39	G2	**Scetan**	Tigray	*Western*	13°28'N 37°33'E
10	C4	**Sciatta**	SNNPR	*Konta*	6°45'N 36°30'E
39	G2	**Scirella**	Tigray	*Western*	13°37'N 37°32'E
39	G4	**Sdni**	Amhara	*North Gonder*	12°51'N 37°27'E
36	A2	**Sebensa**	Amhara	*North Wollo*	12°7'N 39°35'E
22	E2	**Sebro Terara**	Oromia	*East Hararge*	8°48'N 41°36'E
10	B1	**Seccia**	Oromia	*Jimma*	7°45'N 36°10'E
40	B2	**Sechenchen**	Tigray	*North Western*	13°31'N 38°36'E
9	I1	**Seima**	SNNPR	*Kaffa*	7°50'N 35°44'E
9	G5	**Semab**	Gambella	*Agnuak*	6°35'N 35°8'E
33	I3	**Sena**	Amhara	*West Gojam*	11°33'N 36°49'E
11	G2	**Sengiya Terara**	SNNPR	*Hadiya*	7°20'N 37°35'E
10	D1	**Sentama**	Oromia	*Jimma*	7°43'N 36°38'E
37	J2	**Serba Terara**	Afar	*Awsi (Zone 1)*	11°50'N 41°52'E
39	I2	**Serchebin**	Tigray	*North Western*	13°28'N 37°56'E
31	G5	**Serita Terara**	Oromia	*East Hararge*	9°30'N 42°19'E
9	J5	**Shasha**	SNNPR	*Bench Maji*	6°26'N 35°53'E
21	H5	**Sheh Adere Terara**	Oromia	*Arsi*	8°6'N 40°6'E
38	C3	**Sheh Umer**	Amhara	*North Gonder*	12°59'N 36°34'E
3	I2	**Shengema YeTerara Senselet**	SNNPR	*Gamo Gofa*	5°58'N 36°45'E
11	H2	**Shenk'ola Terara**	SNNPR	*Hadiya*	7°26'N 37°45'E
26	C5	**Shenkori Terara**	Benishangul Gumuz	*Kemashi*	9°26'N 36°24'E
31	J3	**Sheyle**	Somali	*Fafan*	10°8'N 42°57'E
19	G5	**Shiro**	Oromia	*Jimma*	8°1'N 37°34'E
4	E2	**Shole YeTerara Senselet**	SNNPR	*Gedio*	5°57'N 38°13'E
4	E1	**Shomb YeTerara Senselet**	Oromia	*Borena*	6°21'N 38°11'E
10	E4	**Shurshomo**	SNNPR	*Dawro*	6°49'N 37°1'E
10	B3	**Sido**	SNNPR	*Kaffa*	7°10'N 36°20'E
36	E1	**Sifeni**	Afar	*Fenti (Zone 4)*	12°15'N 40°27'E
33	H5	**Sigadi**	Amhara	*Awi/Agew*	10°56'N 36°40'E
35	I1	**Sigit**	Amhara	*Wag Himra*	12°11'N 39°5'E
3	H2	**Siki**	SNNPR	*South Omo*	5°55'N 36°40'E
4	C4	**Sillia**	SNNPR	*Segen Peoples'*	5°24'N 37°47'E
25	G5	**Simalla**	Oromia	*West Wellega*	9°23'N 35°8'E
17	F2	**Sira**	Oromia	*Kelem Wellega*	8°57'N 34°50'E
25	H4	**Sirba**	Benishangul Gumuz	*Kemashi*	9°54'N 35°23'E
32	E5	**Sirba**	Benishangul Gumuz	*Metekel*	10°54'N 35°47'E
25	J3	**Sirbanti Terara**	Benishangul Gumuz	*Metekel*	10°9'N 35°52'E
9	I4	**Sire**	SNNPR	*Bench Maji*	6°45'N 35°36'E
21	G3	**Sirri**	Oromia	*Arsi*	8°29'N 39°47'E
35	J2	**Socona**	Amhara	*North Wollo*	12°6'N 39°26'E
18	E2	**Socso**	Oromia	*East Wellega*	8°50'N 36°58'E
18	E2	**Soddu**	Oromia	*East Wellega*	8°54'N 36°56'E
26	B3	**Soghidda**	Oromia	*East Wellega*	10°2'N 36°15'E
19	G1	**Soke Terara**	Oromia	*West Shewa*	9°19'N 37°35'E
12	E4	**Somkeru Terara**	Oromia	*West Arsi*	6°49'N 39°16'E
5	G5	**Sonkligala**	Oromia	*Borena*	4°59'N 38°41'E
16	D2	**Sonkoy**	Oromia	*Kelem Wellega*	9°4'N 34°30'E
31	J5	**Souboul Hanfele**	Somali	*Fafan*	9°35'N 43°0'E
4	D3	**Soyema YeTerara Senselet**	SNNPR	*Segen Peoples'*	5°45'N 37°50'E
40	C5	**Su Amba**	Amhara	*Wag Himra*	12°27'N 38°57'E
20	B1	**Sululta**	Oromia	*North Shewa (R4)*	9°11'N 38°39'E
37	G5	**Sundi**	Afar	*Gabi (Zone 3)*	10°56'N 41°2'E
5	G1	**Suta**	Oromia	*Guji*	6°17'N 38°35'E

T

9	F2	**Tadi**	Gambella	*Agnuak*	7°20'N 34°49'E
39	G2	**Tagle Gheorghis**	Tigray	*Western*	13°32'N 37°29'E
26	D1	**Taia**	Amhara	*Awi/Agew*	10°51'N 36°45'E
2	C2	**Taigu**	SNNPR	*Bench Maji*	6°1'N 35°23'E
27	I2	**Talo**	Amhara	*East Gojam*	10°36'N 37°54'E
11	G3	**Tambaro**	SNNPR	*Kembata Tembaro*	7°12'N 37°32'E
9	G3	**Tangader**	SNNPR	*Bench Maji*	7°6'N 35°11'E
18	B1	**Tankara**	Benishangul Gumuz	*Kemashi*	9°9'N 36°11'E
35	J1	**Taragana**	Amhara	*North Wollo*	12°11'N 39°27'E
39	G4	**Tarat**	Amhara	*North Gonder*	12°41'N 37°24'E
29	F4	**T'armaber**	Amhara	*North Shewa (R3)*	9°53'N 39°44'E
2	C2	**Taye**	SNNPR	*Bench Maji*	6°5'N 35°20'E
21	F1	**Tedda Mariam**	Amhara	*North Shewa (R3)*	9°13'N 39°31'E
40	E3	**Tegora YeTerara Senselet**	Tigray	*Southern*	13°3'N 39°28'E
21	I3	**Tek'edeyo Terara**	Oromia	*West Hararge*	8°46'N 40°25'E
39	J1	**Tekeze Terara**	Tigray	*North Western*	13°49'N 38°11'E
4	B2	**Tempe Terara**	SNNPR	*Gamo Gofa*	6°1'N 37°20'E
24	E1	**Tenze**	Benishangul Gumuz	*Asosa*	10°39'N 34°38'E
36	A1	**Thec**	Amhara	*North Wollo*	12°18'N 39°39'E
2	D2	**Tiacki**	SNNPR	*Bench Maji*	6°6'N 35°34'E
39	H3	**Tintani**	Amhara	*North Gonder*	13°1'N 37°45'E
2	B2	**Tirmakara**	SNNPR	*Bench Maji*	6°4'N 35°9'E
5	I2	**Toba**	Oromia	*Guji*	6°1'N 39°6'E
39	H3	**Tocri**	Amhara	*North Gonder*	13°9'N 37°46'E
17	F2	**Tonghi**	Oromia	*Kelem Wellega*	8°54'N 34°50'E
39	F3	**Torat**	Amhara	*North Gonder*	13°10'N 37°13'E
22	E2	**Tortora YeTerara Senselet**	Oromia	*East Hararge*	8°58'N 41°38'E
24	C5	**T'osho Terara**	Benishangul Gumuz	*Asosa*	9°31'N 34°9'E
41	F1	**Ts'arya Terara**	Tigray	*Eastern*	13°53'N 39°38'E
40	D4	**Tsellari**	Amhara	*Wag Himra*	12°50'N 39°0'E
41	F5	**Tsoiag**	Tigray	*Southern*	12°32'N 39°35'E
38	E1	**Tucul Duma**	Tigray	*Western*	13°52'N 36°58'E
2	B3	**Tulga**	SNNPR	*Bench Maji*	5°41'N 35°8'E
19	I2	**Tuli**	Oromia	*West Shewa*	9°4'N 37°56'E
19	F1	**Tulu Amara Terara**	Oromia	*Horo Guduru*	9°11'N 37°17'E
13	G4	**Tulu Dimtu**	Oromia	*Bale*	6°50'N 39°49'E
25	F5	**Tulu Arba**	Oromia	*West Wellega*	9°23'N 34°50'E
16	D4	**Tulu Aro**	Gambella	*Agnuak*	8°25'N 34°29'E
28	A3	**Tulu Bedada**	Oromia	*North Shewa (R4)*	9°59'N 38°20'E
17	G3	**Tulu Benni**	Oromia	*Ilubabor*	8°36'N 35°11'E
16	E3	**Tulu Cachir**	Oromia	*Kelem Wellega*	8°29'N 34°33'E
13	H1	**Tulu Daltu**	Oromia	*Arsi*	7°43'N 40°12'E
17	F2	**Tulu Deibia**	Oromia	*Kelem Wellega*	9°4'N 34°57'E
25	I5	**Tulu Eriwani**	Oromia	*West Wellega*	9°27'N 35°38'E
16	D3	**Tulu Gallaciu**	Oromia	*Kelem Wellega*	8°39'N 34°30'E
34	C1	**Tulu Ghereccia**	Amhara	*North Gonder*	12°16'N 37°38'E
17	I1	**Tulu Ghinghi**	Oromia	*West Wellega*	9°21'N 35°40'E
26	E5	**Tulu Gudene Terara**	Oromia	*Horo Guduru*	9°31'N 37°5'E
16	D2	**Tulu Inghi**	Benishangul Gumuz	*Asosa*	9°0'N 34°26'E
21	F5	**Tulu Sciato**	Oromia	*Arsi*	7°53'N 39°43'E
16	E3	**Tulu Sciau**	Oromia	*Kelem Wellega*	8°33'N 34°32'E
24	E4	**Tulu Sciava**	Benishangul Gumuz	*Asosa*	9°41'N 34°38'E
24	E4	**Tulu Sida**	Benishangul Gumuz	*Asosa*	9°50'N 34°34'E
21	F3	**Tulu Uaba**	Oromia	*Arsi*	8°28'N 39°34'E
25	G4	**Tulu Uandi**	Oromia	*West Wellega*	9°41'N 35°11'E
17	H5	**Tulu Uarc**	Oromia	*Ilubabor*	8°2'N 35°29'E
17	F2	**Tulu Welel**	Oromia	*Kelem Wellega*	8°53'N 34°50'E
11	H3	**Turduna Terara**	SNNPR	*Kembata Tembaro*	7°16'N 37°40'E
2	C3	**Turmu**	SNNPR	*Bench Maji*	5°37'N 35°22'E
39	J1	**Tzembelta**	Tigray	*North Western*	13°51'N 38°15'E
40	D1	**Tzili**	Tigray	*Central*	13°43'N 39°14'E

U

18	B4	**Uace**	Oromia	*Jimma*	8°12'N 36°17'E
34	C1	**Uadagi**	Amhara	*South Gonder*	12°15'N 37°46'E
26	B4	**Uaggi**	Oromia	*East Wellega*	9°42'N 36°18'E

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38	D4	**Uainia**	Amhara	*North Gonder*	12°36'N 36°47'E
34	E5	**Uajzazir**	Amhara	*East Gojam*	11°1'N 38°12'E
18	D2	**Uakorma**	Oromia	*East Wellega*	9°5'N 36°48'E
40	D3	**Ual Casciua**	Amhara	*Wag Himra*	12°59'N 38°59'E
31	H5	**Ualinsi**	Oromia	*East Hararge*	9°32'N 42°25'E
19	I3	**Uarabo**	Oromia	*South West Shewa*	8°31'N 38°5'E
27	H1	**Uari**	Amhara	*East Gojam*	10°46'N 37°43'E
10	E3	**Uarrai**	SNNPR	*Dawro*	7°3'N 37°7'E
39	I3	**Uasange**	Amhara	*North Gonder*	13°10'N 37°56'E
21	G1	**Uasil**	Amhara	*North Shewa (R3)*	9°17'N 39°47'E
41	G3	**Uassi**	Afar	*Kilbati (Zone 2)*	13°12'N 39°52'E
12	C1	**Uayu**	Oromia	*Arsi*	7°48'N 38°45'E
24	E1	**Ube**	Benishangul Gumuz	*Asosa*	10°38'N 34°40'E
20	C2	**Udama**	Oromia	*North Shewa (R4)*	9°8'N 38°53'E
4	E2	**Udicussa**	Oromia	*Borena*	5°57'N 38°9'E
19	F4	**Ueca**	Oromia	*Jimma*	8°20'N 37°17'E
34	D1	**Uenfit**	Amhara	*South Gonder*	12°13'N 37°55'E
26	B3	**Ueni**	Benishangul Gumuz	*Kemashi*	10°4'N 36°11'E
18	E2	**Uera**	Oromia	*East Wellega*	8°56'N 36°56'E
37	I1	**Umbaba**	Afar	*Awsi (Zone 1)*	12°21'N 41°42'E
11	H4	**Umbo**	SNNPR	*Wolayita*	6°46'N 37°51'E
32	D2	**Umin Zenegir**	Amhara	*North Gonder*	11°58'N 35°35'E
30	B4	**Unda Rugdaia**	Somali	*Siti*	9°39'N 41°1'E
22	A2	**Unde**	Oromia	*West Hararge*	9°1'N 40°48'E
37	H1	**Undurur YeTerara Senselet**	Afar	*Awsi (Zone 1)*	12°10'N 41°24'E
8	D3	**Ungwala**	Gambella	*Agnuak*	6°57'N 34°26'E
39	I3	**Uochen**	Amhara	*North Gonder*	13°6'N 37°56'E
36	C3	**Uodedsca**	Afar	*Awsi (Zone 1)*	11°35'N 40°3'E
5	H4	**Uodo**	Oromia	*Guji*	5°20'N 38°56'E
41	H3	**Uogare**	Afar	*Kilbati (Zone 2)*	13°13'N 40°2'E
19	G2	**Uogedi**	Oromia	*West Shewa*	9°0'N 37°28'E
39	H3	**Uoghed**	Amhara	*North Gonder*	13°10'N 37°48'E
11	G5	**Uoide**	SNNPR	*Gamo Gofa*	6°35'N 37°25'E
11	G4	**Uolamo**	SNNPR	*Wolayita*	6°50'N 37°37'E
40	E5	**Uomberat**	Tigray	*Southern*	12°27'N 39°28'E
36	C2	**Uoneds**	Afar	*Fenti (Zone 4)*	12°3'N 40°6'E
11	G5	**Uoscio**	SNNPR	*Gamo Gofa*	6°32'N 37°38'E
29	F4	**Uoti**	Amhara	*North Shewa (R3)*	9°46'N 39°43'E
13	F3	**Urgoma**	Oromia	*West Arsi*	6°59'N 39°37'E
41	J4	**Urikomam Terara**	Afar	*Fenti (Zone 4)*	12°53'N 40°34'E
27	I1	**Urrata**	Amhara	*East Gojam*	10°40'N 37°58'E
27	J4	**Uru**	Oromia	*North Shewa (R4)*	9°45'N 38°15'E
36	D3	**Uruyegifi Terara**	Afar	*Awsi (Zone 1)*	11°47'N 40°22'E
12	C4	**Ussota**	Oromia	*West Arsi*	6°50'N 38°55'E
19	F5	**Utubo**	Oromia	*Jimma*	8°3'N 37°10'E
35	J4	**Uwa Terara**	Amhara	*South Wollo*	11°10'N 39°25'E

V

10	D2	**Vennio**	Oromia	*Jimma*	7°25'N 36°45'E
15	H4	**Viyeleh**	Somali	*Shabelle*	6°39'N 42°31'E

W

41	F3	**Waga'ade Terara**	Tigray	*Southern*	13°4'N 39°41'E
40	E3	**Walk'e Terara**	Tigray	*Southern*	13°10'N 39°20'E
27	F2	**Wamit**	Amhara	*East Gojam*	10°18'N 37°11'E
20	A2	**Wata Dalecha Terara**	Oromia	*West Shewa*	8°57'N 38°28'E
18	C1	**Wata Terara**	Oromia	*East Wellega*	9°20'N 36°27'E
20	B2	**Wech'ech'a YeTerara Senselet**	Oromia	*West Shewa*	8°59'N 38°35'E
31	F5	**Wedaja Terara**	Dire Dawa	*Dire Dawa*	9°35'N 42°3'E
19	H2	**Wedesa**	Oromia	*West Shewa*	9°2'N 37°47'E
35	J2	**Wek'o Terara**	Amhara	*North Wollo*	11°56'N 39°25'E
30	E4	**Welale Terara**	Somali	*Siti*	9°52'N 41°43'E
21	G4	**Welargi Terara**	Oromia	*Arsi*	8°19'N 39°58'E
21	H2	**Weldoyi Terara**	Oromia	*West Hararge*	8°49'N 40°8'E
41	F2	**Wele'a Terara**	Tigray	*Southern*	13°21'N 39°44'E
20	C3	**Werabecha Terara**	Oromia	*East Shewa*	8°41'N 38°56'E
31	G5	**Were Mucha Terara**	Oromia	*East Hararge*	9°31'N 42°11'E
36	B4	**Wereba Abo YeTerara Senselet**	Amhara	*South Wollo*	11°16'N 39°48'E
19	I2	**Werk'e**	Oromia	*West Shewa*	9°5'N 38°8'E
28	E4	**Weyara Amba**	Amhara	*North Shewa (R3)*	9°57'N 39°16'E
40	A3	**Weynobar (Ancua)**	Amhara	*North Gonder*	13°16'N 38°25'E
41	G2	**Womberta**	Tigray	*Eastern*	13°36'N 39°50'E

Y

4	E4	**Yabal**	Oromia	*Borena*	5°17'N 38°6'E
26	B4	**Yaso YeTerara Senselet**	Oromia	*East Wellega*	9°52'N 36°13'E
34	E5	**Yecandach Mountains**	Amhara	*East Gojam*	11°5'N 38°15'E
36	B5	**Yegof Terara**	Amhara	*South Wollo*	11°2'N 39°42'E
9	G2	**Yina Terara**	SNNPR	*Sheka*	7°36'N 35°17'E

Z

39	F3	**Zagol**	Amhara	*North Gonder*	13°17'N 37°17'E
40	A1	**Zana**	Tigray	*North Western*	13°53'N 38°25'E
39	G1	**Zana Terara**	Tigray	*Western*	13°42'N 37°23'E
28	E3	**Zaro Terara**	Amhara	*North Shewa (R3)*	9°58'N 39°20'E
27	I2	**Zaua**	Amhara	*East Gojam*	10°34'N 37°53'E
16	D1	**Zawa Terara**	Oromia	*West Wellega*	9°19'N 34°28'E
39	F1	**Zeba Uonti**	Tigray	*Western*	13°54'N 37°7'E
40	B1	**Zebo**	Tigray	*Central*	13°59'N 38°38'E
39	F2	**Zelal**	Tigray	*Western*	13°36'N 37°18'E
39	G2	**Zerbabit**	Tigray	*Western*	13°31'N 37°30'E
40	E1	**Zeri`a Awro YeTerara Ch'af**	Tigray	*Eastern*	13°54'N 39°22'E
40	C1	**Ziban Amba**	Tigray	*Central*	13°59'N 38°51'E
20	C3	**Zik'wala Terara**	Oromia	*East Shewa*	8°33'N 38°52'E
36	B1	**Zobil**	Amhara	*North Wollo*	12°15'N 39°45'E
39	J5	**Zoz**	Amhara	*North Gonder*	12°24'N 38°10'E
39	J2	**Zufan**	Amhara	*North Gonder*	13°20'N 38°13'E

Towns/Settlements

A

10	E3	**Aba**	SNNPR	*Dawro*	7°10'N 36°54'E
18	B4	**Aba Bor**	Oromia	*Ilubabor*	8°25'N 36°7'E
21	G3	**Abadir**	Oromia	*East Shewa*	8°45'N 39°54'E
18	B4	**Abdela**	Oromia	*Ilubabor*	8°22'N 36°14'E
38	C1	**Abderafi**	Tigray	*Western*	13°42'N 36°28'E
12	A4	**Abela Lida**	SNNPR	*Sidama*	6°56'N 38°28'E
19	G4	**Abelti**	Oromia	*Jimma*	8°10'N 37°33'E
40	D3	**Aberqele**	Tigray	*Southern*	13°2'N 39°59'E
40	D2	**Abiy Adi**	Tigray	*Central*	13°37'N 38°59'E
8	E1	**Abobo**	Gambella	*Agnuak*	7°54'N 34°32'E
21	G3	**Abomsa**	Oromia	*Arsi*	8°29'N 39°49'E
20	B5	**Abosa**	Oromia	*East Shewa*	8°1'N 38°43'E
27	F4	**Achane**	Oromia	*Horo Guduru*	9°39'N 37°19'E
27	I1	**Achewa Bado**	Amhara	*East Gojam*	10°49'N 38°1'E
26	E1	**Achigi**	Amhara	*West Gojam*	10°43'N 36°57'E
12	E3	**Adaba**	Oromia	*West Arsi*	7°0'N 39°23'E
20	E3	**Adama (Nazret)**	Oromia	*East Shewa*	8°32'N 39°16'E
18	C2	**Adami**	Oromia	*East Wellega*	9°5'N 36°28'E
12	B1	**Adami Tulu**	Oromia	*East Shewa*	7°51'N 38°42'E
20	C2	**ADDIS ABABA**	Addis Ababa	*Region 14*	9°1'N 38°45'E
13	G1	**Adele**	Oromia	*Arsi*	7°46'N 39°54'E
34	B4	**Adet**	Amhara	*West Gojam*	11°15'N 37°29'E
39	I2	**Adi Arkay**	Amhara	*North Gonder*	13°27'N 38°3'E
31	F2	**Adi Gala**	Somali	*Siti*	10°27'N 41°56'E
41	F3	**Adi Gudom**	Tigray	*Southern*	13°15'N 39°31'E
39	F1	**Adi Remets**	Tigray	*Western*	13°44'N 37°19'E
41	F4	**Adi Shoh**	Tigray	*Southern*	12°51'N 39°33'E
39	G3	**Adi Teweld Medhin**	Amhara	*North Gonder*	13°17'N 37°23'E
40	D3	**Adi Zeyla**	Tigray	*Southern*	13°6'N 39°1'E
31	G2	**Adigala**	Somali	*Siti*	10°25'N 42°14'E
20	A2	**Adis Alem**	Oromia	*West Shewa*	9°2'N 38°24'E
21	F3	**Adis Hiywet**	Oromia	*Arsi*	8°31'N 39°35'E
33	I5	**Adis Kidane**	Amhara	*Awi/Agew*	11°5'N 36°53'E
34	C2	**Adis Zemen**	Amhara	*South Gonder*	12°7'N 37°46'E
20	C3	**Adulala**	Oromia	*East Shewa*	8°32'N 38°54'E
30	B5	**Afdem**	Somali	*Siti*	9°28'N 40°59'E
13	G3	**Agarfa**	Oromia	*Bale*	7°16'N 39°49'E
10	C1	**Agaro**	Oromia	*Jimma*	7°51'N 36°35'E
26	E3	**Agemsa**	Oromia	*Horo Guduru*	10°8'N 36°56'E

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19	I4	**Agena**	SNNPR	*Gurage*	8°08'N 38°00'E
4	E3	**Agere Mariyam**	Oromia	*Borena*	5°38'N 38°14'E
18	C5	**Ageyo**	Oromia	*Ilubabor*	8°2'N 36°27'E
34	C4	**Agta**	Amhara	*West Gojam*	11°20'N 37°34'E
41	F1	**Agula**	Tigray	*Eastern*	13°41'N 39°35'E
33	J5	**Agut**	Amhara	*West Gojam*	10°50'N 37°9'E
12	A3	**Aje**	Oromia	*West Arsi*	7°17'N 38°21'E
35	G5	**Ajibar**	Amhara	*South Wollo*	10°51'N 38°35'E
20	C2	**Akaki Beseka**	Addis Ababa	*Region 14*	8°52'N 38°47'E
41	F5	**Alamata**	Tigray	*Southern*	12°24'N 39°33'E
20	D1	**Aleltu**	Oromia	*North Shewa (R4)*	9°11'N 39°9'E
20	B2	**Alem Gena**	Oromia	*South West Shewa*	8°55'N 38°39'E
28	D3	**Alem Ketema**	Amhara	*North Shewa (R3)*	10°3'N 39°0'E
31	F5	**Alem Maya**	Oromia	*East Hararge*	9°23'N 42°1'E
17	G2	**Alem Teferi**	Oromia	*Kelem Wellega*	8°54'N 35°13'E
20	C4	**Alem Tena**	Oromia	*East Shewa*	8°17'N 38°56'E
12	A5	**Aleta Wendo**	SNNPR	*Sidama*	6°36'N 38°25'E
18	E3	**Alga**	Oromia	*Jimma*	8°35'N 37°6'E
17	I3	**Alge**	Oromia	*Ilubabor*	8°35'N 35°44'E
13	G3	**Ali**	Oromia	*Bale*	7°14'N 39°55'E
28	B4	**Ali Doro**	Oromia	*North Shewa (R4)*	9°46'N 38°31'E
26	E4	**Alibo**	Oromia	*Horo Guduru*	9°53'N 37°4'E
29	G5	**Aliyu Amba**	Amhara	*North Shewa (R3)*	9°34'N 39°48'E
5	G3	**Alona**	Oromia	*Guji*	5°45'N 38°40'E
27	G2	**Amanuel**	Amhara	*East Gojam*	10°26'N 37°34'E
39	G4	**Amba Giyorgis**	Amhara	*North Gonder*	12°46'N 37°37'E
35	H3	**Amba Lamba**	Amhara	*North Wollo*	11°41'N 39°2'E
41	F4	**Ambalage**	Tigray	*Southern*	12°56'N 39°31'E
19	H2	**Ambo**	Oromia	*West Shewa*	8°58'N 37°51'E
18	E5	**Ambuye**	Oromia	*Jimma*	7°58'N 36°54'E
40	B5	**Amde Werk**	Amhara	*Wag Himra*	12°26'N 38°43'E
34	D2	**Amed Ber**	Amhara	*South Gonder*	11°54'N 37°53'E
10	D3	**Ameya**	SNNPR	*Konta*	7°6'N 36°40'E
33	I2	**Amistiya**	Amhara	*North Gonder*	12°1'N 36°55'E
34	C3	**Anbesame**	Amhara	*South Gonder*	11°42'N 37°37'E
36	B5	**Ancharo**	Amhara	*South Wollo*	11°2'N 39°46'E
28	E4	**Anchekorer**	Amhara	*North Shewa (R3)*	9°48'N 39°17'E
10	B3	**Anderacha**	SNNPR	*Kaffa*	7°12'N 36°16'E
21	G4	**Angada**	Oromia	*Arsi*	8°23'N 39°49'E
11	H3	**Angecha**	SNNPR	*Kembata Tembaro*	7°12'N 37°46'E
27	G1	**Anjeni**	Amhara	*West Gojam*	10°40'N 37°32'E
29	F5	**Ankober**	Amhara	*North Shewa (R3)*	9°35'N 39°44'E
18	E2	**Ano**	Oromia	*East Wellega*	9°5'N 36°57'E
12	A4	**Aposto**	SNNPR	*Sidama*	6°44'N 38°22'E
31	I4	**Arabi**	Somali	*Siti*	9°55'N 42°42'E
34	C3	**Arb Gebeya**	Amhara	*South Gonder*	11°38'N 37°44'E
4	B2	**Arba Minch**	SNNPR	*Gamo Gofa*	6°1'N 37°33'E
22	B2	**Arba Reketi**	Oromia	*West Hararge*	9°3'N 40°54'E
12	B4	**Arbe Gona**	SNNPR	*Sidama*	6°41'N 38°43'E
21	F4	**Arboye**	Oromia	*Arsi*	8°22'N 39°40'E
11	H3	**Areka**	SNNPR	*Wolayita*	7°4'N 37°42'E
20	E2	**Arerti**	Amhara	*North Shewa (R3)*	8°55'N 39°25'E
4	B3	**Arguba**	SNNPR	*Segen Peoples'*	5°44'N 37°23'E
18	B2	**Arjo**	Oromia	*East Wellega*	9°2'N 36°14'E
18	C3	**Arjo**	Oromia	*East Wellega*	8°45'N 36°30'E
19	I5	**Arkit**	SNNPR	*Gurage*	8°0'N 38°6'E
29	G4	**Armanaya**	Amhara	*North Shewa (R3)*	9°52'N 39°49'E
12	B2	**Arsi Negele**	Oromia	*West Arsi*	7°21'N 38°40'E
21	F1	**Asagirt**	Amhara	*North Shewa (R3)*	9°24'N 39°35'E
37	H3	**Asayita**	Afar	*Awsi (Zone 1)*	11°34'N 41°26'E
22	B2	**Asbe Teferi**	Oromia	*West Hararge*	9°4'N 40°51'E
30	C3	**Asbuli**	Somali	*Siti*	9°58'N 41°9'E
11	F1	**Asendabo**	Oromia	*Jimma*	7°45'N 37°13'E
16	E3	**Ashi (Sedi)**	Oromia	*Kelem Wellega*	8°39'N 34°42'E
40	D5	**Asketema**	Amhara	*Wag Himra*	12°24'N 39°0'E
24	E3	**ASOSA**	Benishangul Gumuz	*Asosa*	10°3'N 34°32'E
12	D3	**Assasa**	Oromia	*West Arsi*	7°6'N 39°11'E
20	D5	**Assela**	Oromia	*Arsi*	7°57'N 39°7'E
29	G2	**Ataye**	Amhara	*North Shewa (R3)*	10°21'N 39°56'E
18	E4	**Atnago**	Oromia	*Jimma*	8°18'N 36°56'E
41	F1	**Atsbi Inda Silase**	Tigray	*Eastern*	13°51'N 39°43'E
21	H2	**Awash**	Afar	*Gabi (Zone 3)*	8°59'N 40°9'E
26	D4	**Ayana**	Oromia	*East Wellega*	9°52'N 36°37'E
30	D4	**Aydora**	Somali	*Siti*	9°51'N 41°22'E
31	H1	**Ayisha**	Somali	*Siti*	10°45'N 42°34'E
38	E5	**Aykel**	Amhara	*North Gonder*	12°30'N 37°2'E
35	H1	**Ayna**	Amhara	*North Wollo*	12°9'N 38°51'E
26	D1	**Azena**	Amhara	*Awi/Agew*	10°45'N 36°48'E
39	G5	**Azezo**	Amhara	*North Gonder*	12°32'N 37°25'E

B

23	G1	**Babile**	Oromia	*East Hararge*	9°12'N 42°21'E
18	E4	**Babo**	Oromia	*Jimma*	8°10'N 36°55'E
9	J4	**Bachuma**	SNNPR	*Bench Maji*	6°49'N 35°54'E
34	B3	**BAHIR DAR**	Amhara	*West Gojam*	11°35'N 37°22'E
18	E2	**Bako**	Oromia	*West Shewa*	9°7'N 37°3'E
3	H2	**Bako**	SNNPR	*South Omo*	5°50'N 36°37'E
20	E2	**Balchi**	Amhara	*North Shewa (R3)*	8°54'N 39°22'E
24	E4	**Bambesi**	Benishangul Gumuz	*Asosa*	9°45'N 34°43'E
18	C2	**Bandiro**	Oromia	*East Wellega*	8°55'N 36°35'E
20	A3	**Bantu**	Oromia	*South West Shewa*	8°36'N 38°22'E
36	C4	**Bati**	Amhara	*Oromia*	11°11'N 40°1'E
9	H4	**Bebeka**	SNNPR	*Bench Maji*	6°51'N 35°20'E
17	I4	**Becho**	Oromia	*Ilubabor*	8°12'N 35°41'E
18	B3	**Bedele**	Oromia	*Ilubabor*	8°27'N 36°21'E
22	E2	**Bedeno**	Oromia	*East Hararge*	9°6'N 41°37'E
22	A2	**Bedesa**	Oromia	*West Hararge*	8°54'N 40°46'E
11	I4	**Bedesa**	SNNPR	*Wolayita*	6°52'N 37°56'E
18	E4	**Bege**	Oromia	*Jimma*	8°18'N 37°6'E
16	E1	**Begi**	Oromia	*West Wellega*	9°20'N 34°32'E
4	B4	**Bekawile (Konso)**	SNNPR	*Segen Peoples'*	5°20'N 37°26'E
12	E2	**Bekoji**	Oromia	*Arsi*	7°31'N 39°15'E
13	H1	**Bele**	Oromia	*Arsi*	7°43'N 39°59'E
11	G4	**Bele**	SNNPR	*Wolayita*	6°55'N 37°31'E
5	I3	**Belesa Koricha**	Oromia	*Guji*	5°47'N 39°4'E
4	A2	**Belta**	SNNPR	*Gamo Gofa*	6°3'N 37°16'E
25	F4	**Benguwa**	Oromia	*West Wellega*	9°46'N 34°54'E
41	G1	**Berahile**	Afar	*Kilbati (Zone 2)*	13°51'N 40°0'E
10	C1	**Beshash**	Oromia	*Jimma*	7°47'N 36°28'E
35	H3	**Bete Hor**	Amhara	*North Wollo*	11°40'N 38°49'E
27	H3	**Bete Nigus**	Amhara	*East Gojam*	9°58'N 37°47'E
3	I2	**Beto**	SNNPR	*Gamo Gofa*	6°3'N 36°52'E
27	J2	**Bichena**	Amhara	*East Gojam*	10°27'N 38°12'E
19	I1	**Bicho**	Oromia	*West Shewa*	9°15'N 38°1'E
6	A3	**Bidire**	Oromia	*Bale*	5°47'N 39°32'E
18	C4	**Bido**	Oromia	*Ilubabor*	8°13'N 36°26'E
30	C5	**Bike**	Somali	*Siti*	9°31'N 41°12'E
18	E1	**Bila**	Oromia	*East Wellega*	9°17'N 37°1'E
25	I5	**Bila**	Oromia	*West Wellega*	9°22'N 35°35'E
18	E2	**Bilo**	Oromia	*East Wellega*	8°53'N 37°0'E
35	I2	**Bir Afaf**	Amhara	*North Wollo*	11°51'N 39°8'E
4	C1	**Birbir**	SNNPR	*Gamo Gofa*	6°18'N 37°46'E
17	G5	**Birbirsa**	Oromia	*Ilubabor*	8°3'N 35°9'E
5	G3	**Birbirsa Bera**	Oromia	*Guji*	5°42'N 38°35'E
27	J4	**Biriti**	Oromia	*North Shewa (R4)*	9°45'N 38°16'E
9	I3	**Bita Genet**	SNNPR	*Kaffa*	7°16'N 35°46'E
6	A3	**Bitata**	Oromia	*Guji*	5°28'N 39°28'E
19	G1	**Bitile**	Oromia	*West Shewa*	9°11'N 37°28'E
31	H3	**Biye Anod**	Somali	*Siti*	10°3'N 42°31'E
31	H2	**Biye Gurgur**	Somali	*Siti*	10°23'N 42°34'E
11	I3	**Boditi**	SNNPR	*Wolayita*	6°57'N 37°51'E
23	F2	**Boku**	Oromia	*East Hararge*	9°7'N 42°5'E
4	D5	**Bolekedo**	Oromia	*Borena*	4°57'N 37°59'E
10	E2	**Boneya**	Oromia	*Jimma*	7°32'N 37°3'E
20	B2	**Boneya**	Oromia	*South West Shewa*	8°49'N 38°38'E
17	F4	**Bonga**	Gambella	*Agnuak*	8°10'N 34°50'E
10	B3	**Bonga**	SNNPR	*Kaffa*	7°16'N 36°15'E
4	B2	**Bonke Beza**	SNNPR	*Gamo Gofa*	6°3'N 37°20'E
21	I2	**Bordele**	Oromia	*West Hararge*	9°1'N 40°23'E
12	B5	**Bore**	Oromia	*Guji*	6°21'N 38°37'E
36	A4	**Boru**	Amhara	*South Wollo*	11°13'N 39°39'E
19	F4	**Botor Bocho**	Oromia	*Jimma*	8°22'N 37°16'E
19	F4	**Botor Keta**	Oromia	*Jimma*	8°22'N 37°19'E
17	J2	**Bube**	Oromia	*West Wellega*	8°50'N 35°48'E

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20	B4	**Bu-i**	SNNPR	*Gurage*	8°19'N 38°32'E
21	F5	**Bulala**	Oromia	*Arsi*	7°59'N 39°34'E
12	B1	**Bulbula**	Oromia	*East Shewa*	7°43'N 38°39'E
5	A5	**Bule**	Oromia	*Guji*	6°16'N 38°27'E
12	D5	**Bulega**	SNNPR	*Sidama*	6°35'N 39°6'E
26	A2	**Bulen**	Benishangul Gumuz	*Metekel*	10°35'N 36°4'E
3	I1	**Bulki**	SNNPR	*Gamo Gofa*	6°16'N 36°48'E
12	A3	**Bura**	Oromia	*West Arsi*	7°15'N 38°29'E
26	E1	**Bure**	Amhara	*West Gojam*	10°43'N 37°4'E
17	G4	**Bure**	Oromia	*Ilubabor*	8°17'N 35°6'E
17	H4	**Burusa**	Oromia	*Ilubabor*	8°17'N 35°27'E
20	A4	**Butajira**	SNNPR	*Gurage*	8°7'N 38°22'E

C

28	E5	**Chacha**	Amhara	*North Shewa (R3)*	9°32'N 39°27'E
33	H5	**Chagni**	Amhara	*Awi/Agew*	10°57'N 36°30'E
20	C1	**Chancho**	Oromia	*North Shewa (R4)*	9°18'N 38°45'E
38	E5	**Chandiba**	Amhara	*North Gonder*	12°23'N 37°1'E
17	G2	**Chanka**	Oromia	*Kelem Wellega*	8°51'N 35°4'E
20	D2	**Chefe Donsa**	Oromia	*East Shewa*	8°58'N 39°7'E
5	H3	**Cheketa**	Oromia	*Guji*	5°39'N 38°49'E
21	H3	**Chelekko**	Oromia	*West Hararge*	8°41'N 40°14'E
4	E2	**Chelelektu**	SNNPR	*Gedio*	6°1'N 38°9'E
30	D5	**Chelenko**	Oromia	*East Hararge*	9°23'N 41°33'E
27	H3	**Chemoga**	Amhara	*East Gojam*	10°18'N 37°45'E
4	C1	**Chencha**	SNNPR	*Gamo Gofa*	6°15'N 37°34'E
39	J3	**Chennek**	Amhara	*North Gonder*	13°15'N 38°11'E
7	J4	**Chereti**	Somali	*Afder*	5°20'N 41°53'E
10	D3	**Chida**	SNNPR	*Konta*	7°10'N 36°47'E
31	H5	**Chinaksen**	Oromia	*East Hararge*	9°31'N 42°33'E
10	B1	**Chira**	Oromia	*Jimma*	7°44'N 36°15'E
10	B3	**Chiri**	SNNPR	*Kaffa*	7°7'N 36°11'E
19	I1	**Chobi**	Oromia	*West Shewa*	9°19'N 37°56'E
18	D5	**Choche**	Oromia	*Jimma*	7°57'N 36°42'E
21	G4	**Chole**	Oromia	*Arsi*	8°8'N 39°54'E
12	A4	**Chuko**	SNNPR	*Sidama*	6°39'N 38°21'E
27	H4	**Chulute**	Oromia	*West Shewa*	9°39'N 37°44'E
34	A1	**Chwahit Mender**	Amhara	*North Gonder*	12°19'N 37°13'E

D

39	H3	**Dabat**	Amhara	*North Gonder*	12°58'N 37°45'E
34	B5	**Dabi**	Amhara	*West Gojam*	10°59'N 37°25'E
40	C5	**Dahana**	Amhara	*Wag Himra*	12°27'N 38°51'E
25	G3	**Daleti**	Benishangul Gumuz	*Asosa*	10°1'N 35°13'E
28	B4	**Daleti**	Oromia	*North Shewa (R4)*	9°36'N 38°35'E
11	J5	**Dalocha**	SNNPR	*Selti*	7°47'N 38°14'E
33	I4	**Dangla**	Amhara	*Awi/Agew*	11°15'N 36°50'E
10	A2	**Dara**	SNNPR	*Kaffa*	7°18'N 35°59'E
5	G4	**Dawa**	Oromia	*Guji*	5°19'N 38°47'E
17	F2	**Dawo Kebe**	Oromia	*Kelem Wellega*	8°58'N 34°58'E
39	I3	**Debark**	Amhara	*North Gonder*	13°9'N 37°53'E
25	G5	**Debeka**	Oromia	*West Wellega*	9°28'N 35°11'E
29	I3	**Debel**	Afar	*Hari (Zone 5)*	10°15'N 40°15'E
17	I2	**Debeso**	Oromia	*West Wellega*	8°50'N 35°39'E
17	I1	**Deboko**	Oromia	*West Wellega*	9°16'N 35°41'E
28	B5	**Debra**	Oromia	*North Shewa (R4)*	9°26'N 38°38'E
29	F4	**Debre Birhan**	Amhara	*North Shewa (R3)*	9°40'N 39°31'E
20	A3	**Debre Genet**	Oromia	*South West Shewa*	8°47'N 38°19'E
28	C4	**Debre Libanos**	Oromia	*North Shewa (R4)*	9°42'N 38°50'E
27	H2	**Debre Markos**	Amhara	*East Gojam*	10°20'N 37°43'E
29	G4	**Debre Sina**	Amhara	*North Shewa (R3)*	9°50'N 39°45'E
34	D2	**Debre Tabor**	Amhara	*South Gonder*	11°51'N 38°0'E
28	C4	**Debre Tsige**	Oromia	*North Shewa (R4)*	9°38'N 38°50'E
27	J1	**Debre Werk**	Amhara	*East Gojam*	10°39'N 38°9'E
35	G2	**Debre Zebit**	Amhara	*North Wollo*	11°49'N 38°36'E
25	I2	**Debre Zeyit (Wembera)**	Benishangul Gumuz	*Metekel*	10°37'N 35°39'E
20	D3	**Debre Zeyt (Bishoftu)**	Oromia	*East Shewa*	8°44'N 38°59'E
37	J2	**Deday**	Afar	*Awsi (Zone 1)*	11°54'N 41°47'E
22	D5	**Deder**	Oromia	*East Hararge*	9°18'N 41°26'E
4	D4	**Dedertu**	Oromia	*Borena*	5°13'N 38°2'E
10	D2	**Dedo**	Oromia	*Jimma*	7°30'N 36°52'E
27	G4	**Dedu**	Oromia	*Horo Guduru*	9°41'N 37°32'E
18	A3	**Dega**	Oromia	*Ilubabor*	8°34'N 36°6'E
12	C2	**Degaga**	Oromia	*West Arsi*	7°25'N 38°48'E
23	J5	**Degeh Medo**	Somali	*Jarar*	7°59'N 43°0'E
28	B4	**Degem**	Oromia	*North Shewa (R4)*	9°48'N 38°37'E
27	J3	**Dejen**	Amhara	*East Gojam*	10°10'N 38°9'E
33	J1	**Delgi**	Amhara	*North Gonder*	12°11'N 37°2'E
27	G2	**Dembecha**	Amhara	*West Gojam*	10°34'N 37°29'E
18	C5	**Dembi**	Oromia	*Ilubabor*	8°5'N 36°27'E
17	F3	**Dembidolo**	Oromia	*Kelem Wellega*	8°32'N 34°48'E
31	I4	**Denbel**	Somali	*Fafan*	9°52'N 42°45'E
28	D4	**Deneba**	Amhara	*North Shewa (R3)*	9°45'N 39°11'E
11	F1	**Deneba**	Oromia	*Jimma*	7°50'N 37°21'E
38	E2	**Densha**	Tigray	*Western*	13°33'N 36°58'E
20	E4	**Dera**	Oromia	*Arsi*	8°19'N 39°19'E
39	J3	**Deresge**	Amhara	*North Gonder*	13°4'N 38°8'E
10	B2	**Deri**	SNNPR	*Kaffa*	7°23'N 36°17'E
36	A4	**Dese**	Amhara	*South Wollo*	11°7'N 39°38'E
39	I3	**Dib Bahir**	Amhara	*North Gonder*	13°14'N 37°53'E
26	B1	**Dibate**	Benishangul Gumuz	*Metekel*	10°46'N 36°15'E
23	F5	**Didimtu**	Oromia	*East Hararge*	9°21'N 42°2'E
12	E1	**Digelu**	Oromia	*Arsi*	7°45'N 39°15'E
27	H1	**Digo Tsiyon**	Amhara	*East Gojam*	10°51'N 37°44'E
15	I3	**Dihun**	Somali	*Nogob*	7°13'N 42°41'E
19	I3	**Dilela**	Oromia	*South West Shewa*	8°38'N 38°3'E
40	A3	**Dilibza**	Amhara	*North Gonder*	13°6'N 38°26'E
12	A5	**Dilla**	SNNPR	*Gedio*	6°24'N 38°18'E
11	F5	**Dimtu**	Oromia	*Jimma*	7°48'N 37°9'E
11	I4	**Dimtu**	SNNPR	*Wolayita*	6°53'N 38°2'E
29	F4	**Dinbaro**	Amhara	*North Shewa (R3)*	9°42'N 39°38'E
21	G3	**Dino**	Oromia	*Arsi*	8°40'N 39°56'E
33	J2	**Dinqil Ber**	Amhara	*North Gonder*	11°58'N 36°59'E
13	G3	**Dinshu**	Oromia	*Bale*	7°6'N 39°46'E
26	D4	**Dire**	Oromia	*East Wellega*	9°55'N 36°40'E
31	F4	**DIRE DAWA**	Dire Dawa	*Dire Dawa*	9°35'N 41°51'E
19	G4	**Dire Godu**	Oromia	*West Shewa*	8°26'N 37°25'E
12	D3	**Dodola**	Oromia	*West Arsi*	6°58'N 39°10'E
28	E2	**Dogolo**	Amhara	*South Wollo*	10°25'N 39°15'E
28	C5	**Duber**	Oromia	*North Shewa (R4)*	9°27'N 38°52'E
37	G3	**Dubti**	Afar	*Awsi (Zone 1)*	11°43'N 41°5'E
20	B4	**Dugda**	SNNPR	*Gurage*	8°10'N 38°38'E
20	C3	**Dukem**	Oromia	*East Shewa*	8°47'N 38°53'E
29	G5	**Dulecha**	Afar	*Gabi (Zone 3)*	9°32'N 39°57'E
17	H3	**Dupa**	Oromia	*Ilubabor*	8°34'N 35°31'E
11	I3	**Durame**	SNNPR	*Kembata Tembaro*	7°14'N 37°54'E
33	J4	**Durbete**	Amhara	*West Gojam*	11°21'N 36°57'E
11	G3	**Durgi**	SNNPR	*Kembata Tembaro*	7°16'N 37°28'E
10	B1	**Dusta**	Oromia	*Jimma*	7°45'N 36°11'E

E

29	G2	**Efeson**	Amhara	*North Shewa (R3)*	10°20'N 39°57'E
20	E3	**Ejere**	Oromia	*East Shewa*	8°46'N 39°15'E
28	B4	**Ejere**	Oromia	*North Shewa (R4)*	9°55'N 38°30'E
17	J3	**Elemo**	Oromia	*Ilubabor*	8°27'N 35°49'E
27	G3	**Eliyas**	Amhara	*East Gojam*	10°17'N 37°27'E
30	D5	**Erer**	Somali	*Siti*	9°32'N 41°21'E

F

4	B4	**Fasha**	SNNPR	*Segen Peoples'*	5°16'N 37°21'E
18	D2	**Fechase**	Oromia	*East Wellega*	8°58'N 36°40'E
27	I1	**Felege Birhan**	Amhara	*East Gojam*	10°44'N 38°3'E
10	C3	**Felege Selam**	SNNPR	*Kaffa*	7°6'N 36°28'E
27	G1	**Feres Bet**	Amhara	*West Gojam*	10°50'N 37°35'E
28	C3	**Fetire**	Amhara	*North Shewa (R3)*	10°0'N 38°53'E
28	C4	**Fiche**	Oromia	*North Shewa (R4)*	9°46'N 38°43'E
23	G4	**Fik**	Somali	*Nogob*	8°8'N 42°18'E
35	G2	**Filakit**	Amhara	*North Wollo*	11°46'N 38°44'E
27	J3	**Filikilik**	Oromia	*North Shewa (R4)*	10°3'N 38°15'E
7	F5	**Filtu**	Somali	*Liben*	5°6'N 40°39'E
27	F5	**Fincha-a**	Oromia	*Horo Guduru*	9°33'N 37°21'E
4	E4	**Finchawa**	Oromia	*Borena*	5°24'N 38°16'E
27	F1	**Finote Selam**	Amhara	*West Gojam*	10°40'N 37°15'E
35	I3	**Firida Mareja**	Amhara	*North Wollo*	11°33'N 39°8'E

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4	E2	**Fiseha Genet**	SNNPR	*Gedio*	6°4'N 38°12'E
11	G5	**Fofa**	SNNPR	*Yem*	7°50'N 37°31'E
33	J5	**Fogota**	Amhara	*Awi/Agew*	11°3'N 37°2'E
11	I2	**Fonko**	SNNPR	*Hadiya*	7°38'N 37°57'E
23	H1	**Funyan Bira**	Oromia	*East Hararge*	9°21'N 42°23'E

G

9	J4	**Gachit**	SNNPR	*Bench Maji*	6°45'N 35°47'E
26	B2	**Galesa**	Benishangul Gumuz	*Metekel*	10°26'N 36°8'E
16	E4	**Gambela**	Gambella	*Agnuak*	8°15'N 34°35'E
16	E3	**Garigeda**	Oromia	*Kelem Wellega*	8°46'N 34°39'E
34	E3	**Gasay**	Amhara	*South Gonder*	11°47'N 38°8'E
13	H2	**Gasera**	Oromia	*Bale*	7°22'N 40°11'E
35	H3	**Gashena**	Amhara	*North Wollo*	11°41'N 38°55'E
18	B5	**Gatira**	Oromia	*Jimma*	8°2'N 36°14'E
4	B3	**Gato**	SNNPR	*Segen Peoples'*	5°33'N 37°24'E
28	A4	**Gebre Guracha**	Oromia	*North Shewa (R4)*	9°48'N 38°25'E
9	H2	**Gecha**	SNNPR	*Sheka*	7°33'N 35°24'E
18	C4	**Gechi**	Oromia	*Ilubabor*	8°20'N 36°25'E
4	E2	**Gedeb**	SNNPR	*Gedio*	5°58'N 38°15'E
39	H4	**Gedebge**	Amhara	*North Gonder*	12°52'N 37°44'E
19	G2	**Gedo**	Oromia	*West Shewa*	9°0'N 37°26'E
21	J2	**Gelemso**	Oromia	*West Hararge*	8°48'N 40°30'E
26	C4	**Gelila**	Oromia	*East Wellega*	9°50'N 36°28'E
10	D1	**Gembe**	Oromia	*Jimma*	7°50'N 36°40'E
11	I3	**Gemesha**	SNNPR	*Kembata Tembaro*	7°14'N 37°54'E
4	B4	**Gemole**	SNNPR	*Segen Peoples'*	5°17'N 37°27'E
28	D3	**Gende Bune**	Amhara	*North Shewa (R3)*	10°15'N 39°9'E
28	C1	**Genet**	Amhara	*South Wollo*	10°46'N 38°50'E
27	G1	**Genet**	Amhara	*West Gojam*	10°49'N 37°25'E
17	I2	**Genji**	Oromia	*West Wellega*	9°2'N 35°36'E
10	D3	**Genji**	SNNPR	*Konta*	7°7'N 36°45'E
18	E5	**Gent**	Oromia	*Jimma*	8°5'N 36°56'E
4	E3	**Gerba**	Oromia	*Borena*	5°46'N 38°16'E
4	A2	**Gerese**	SNNPR	*Gamo Gofa*	5°55'N 37°17'E
18	B4	**Gesecha**	Oromia	*Jimma*	8°8'N 36°9'E
9	H5	**Gesha**	SNNPR	*Bench Maji*	6°33'N 35°30'E
11	G4	**Gesuba**	SNNPR	*Wolayita*	6°47'N 37°33'E
18	C2	**Getema**	Oromia	*East Wellega*	8°53'N 36°29'E
4	A4	**Gewada**	SNNPR	*Segen Peoples'*	5°25'N 37°14'E
29	J3	**Gewane**	Afar	*Gabi (Zone 3)*	10°9'N 40°39'E
11	F1	**Gibe**	Oromia	*Jimma*	7°45'N 37°11'E
39	I3	**Gich**	Amhara	*North Gonder*	13°16'N 38°6'E
16	E2	**Gidami**	Oromia	*Kelem Wellega*	8°59'N 34°36'E
4	I5	**Gidicho**	Oromia	*Borena*	6°22'N 37°57'E
4	B3	**Gidole**	SNNPR	*Segen Peoples'*	5°38'N 37°20'E
17	J1	**Gimbi**	Oromia	*West Wellega*	9°10'N 35°50'E
11	G2	**Gimbichu**	SNNPR	*Hadiya*	7°26'N 37°37'E
12	E2	**Gimbite**	Oromia	*Arsi*	7°20'N 39°22'E
10	B2	**Gimbo**	SNNPR	*Kaffa*	7°23'N 36°13'E
33	I5	**Gimja Bet**	Amhara	*Awi/Agew*	10°51'N 36°53'E
21	F1	**Gina Ager**	Amhara	*North Shewa (R3)*	9°20'N 39°34'E
19	I2	**Ginchi**	Oromia	*West Shewa*	9°1'N 38°7'E
14	A3	**Ginir**	Oromia	*Bale*	7°8'N 40°42'E
22	E2	**Girawa**	Oromia	*East Hararge*	9°8'N 41°50'E
34	A5	**Gish Abay**	Amhara	*West Gojam*	10°59'N 37°13'E
35	J3	**Gishen Maryam**	Amhara	*South Wollo*	11°31'N 39°21'E
25	F1	**Gizen**	Benishangul Gumuz	*Asosa*	10°42'N 34°46'E
13	G3	**Goba**	Oromia	*Bale*	7°1'N 39°58'E
19	F1	**Goben**	Oromia	*Horo Guduru*	9°10'N 37°18'E
13	F2	**Gobesa**	Oromia	*Arsi*	7°36'N 39°29'E
4	D3	**Goche**	SNNPR	*Segen Peoples'*	5°32'N 37°54'E
25	G2	**Godere**	Benishangul Gumuz	*Kemashi*	10°26'N 35°7'E
20	D2	**Godino**	Oromia	*East Shewa*	8°52'N 39°1'E
29	F4	**Godo Beret**	Amhara	*North Shewa (R3)*	9°48'N 39°41'E
31	I3	**Gogti**	Somali	*Fafan*	10°4'N 42°50'E
19	I1	**Goja**	Oromia	*West Shewa*	9°16'N 38°3'E
19	J1	**Gola**	Oromia	*West Shewa*	9°18'N 38°11'E
18	C1	**Golo**	Oromia	*East Wellega*	9°10'N 36°27'E
21	H4	**Gololcha**	Oromia	*Arsi*	8°11'N 40°3'E
26	D2	**Gomer**	Amhara	*West Gojam*	10°25'N 36°51'E
20	D5	**Gonde**	Oromia	*Arsi*	8°1'N 39°10'E
39	G4	**Gonder**	Amhara	*North Gonder*	12°36'N 37°28'E
34	C4	**Gonj**	Amhara	*West Gojam*	11°13'N 37°40'E
17	H4	**Gore**	Oromia	*Ilubabor*	8°9'N 35°32'E
28	C5	**Gorfo**	Oromia	*North Shewa (R4)*	9°23'N 38°50'E
34	B1	**Gorgora**	Amhara	*North Gonder*	12°14'N 37°18'E
13	J4	**Goro**	Oromia	*Bale*	6°57'N 40°37'E
27	J3	**Gosha Tsiyon**	Oromia	*North Shewa (R4)*	10°0'N 38°14'E
30	C5	**Gota**	Somali	*Siti*	9°31'N 41°19'E
10	D3	**Gowa**	SNNPR	*Konta*	7°2'N 36°39'E
32	C4	**Guba**	Benishangul Gumuz	*Metekel*	11°16'N 35°17'E
19	H4	**Gubre**	SNNPR	*Gurage*	8°10'N 37°48'E
19	H2	**Guder**	Oromia	*West Shewa*	8°58'N 37°45'E
12	B3	**Guguma**	SNNPR	*Sidama*	6°58'N 38°42'E
39	I5	**Guhala**	Amhara	*North Gonder*	12°24'N 38°4'E
17	J2	**Guji**	Oromia	*West Wellega*	9°0'N 35°49'E
17	H1	**Guliso**	Oromia	*West Wellega*	9°9'N 35°28'E
19	H5	**Gunchire**	SNNPR	*Gurage*	8°1'N 37°50'E
34	E5	**Gunde Weyn**	Amhara	*East Gojam*	10°55'N 38°5'E
28	B3	**Gundo Meskel**	Oromia	*North Shewa (R4)*	10°13'N 38°41'E
9	G4	**Gura Ferda**	SNNPR	*Bench Maji*	6°49'N 35°6'E
18	D2	**Gute**	Oromia	*East Wellega*	9°1'N 36°37'E
18	B3	**Guto**	Oromia	*Ilubabor*	8°38'N 36°10'E
34	D1	**Gwaliya**	Amhara	*South Gonder*	12°10'N 37°59'E

H

13	G1	**Habe**	Oromia	*Arsi*	7°49'N 39°47'E
14	D2	**Hada**	Oromia	*Bale*	7°21'N 41°21'E
23	I1	**Hadew**	Somali	*Fafan*	9°22'N 42°40'E
12	B5	**Hagere Selam**	SNNPR	*Sidama*	6°29'N 38°31'E
40	D2	**Hagere Selam**	Tigray	*Central*	13°39'N 39°10'E
13	F3	**Hako**	Oromia	*West Arsi*	7°9'N 39°32'E
21	F5	**Hamda Diskis**	Oromia	*Arsi*	8°3'N 39°33'E
18	A2	**Hamus Gebeya**	Oromia	*Ilubabor*	9°3'N 36°6'E
19	G2	**Hamus Gebeya**	Oromia	*West Shewa*	9°7'N 37°31'E
34	C3	**Hamusit Mender**	Amhara	*South Gonder*	11°46'N 37°33'E
3	F1	**Hana**	SNNPR	*South Omo*	6°13'N 36°7'E
23	G1	**HARAR**	Hareri	*Hareri*	9°18'N 42°7'E
31	F3	**Harawa**	Somali	*Siti*	9°55'N 41°59'E
22	C1	**Harawacha**	Oromia	*East Hararge*	9°11'N 41°20'E
36	B5	**Harbu**	Amhara	*South Wollo*	10°56'N 39°46'E
5	J3	**Hare Kelo**	Oromia	*Guji*	5°33'N 39°23'E
26	B4	**Haro**	Oromia	*East Wellega*	9°50'N 36°18'E
12	B3	**HAWASSA**	SNNPR	*Sidama*	7°2'N 38°29'E
36	B4	**Hayk**	Amhara	*South Wollo*	11°18'N 39°40'E
37	I2	**Hayu**	Afar	*Awsi (Zone 1)*	11°55'N 41°33'E
17	I1	**Hena**	Oromia	*West Wellega*	9°21'N 35°41'E
28	D2	**Hibino**	Amhara	*South Wollo*	10°27'N 39°0'E
40	E3	**Hintalo**	Tigray	*Southern*	13°14'N 39°25'E
22	C1	**Hirna**	Oromia	*West Hararge*	9°13'N 41°6'E
40	F3	**Hiwane**	Tigray	*Southern*	13°5'N 39°29'E
12	B4	**Hogiso**	SNNPR	*Sidama*	6°50'N 38°40'E
20	B2	**Holota**	Oromia	*West Shewa*	9°4'N 38°29'E
11	H2	**Hosaina**	SNNPR	*Hadiya*	7°32'N 37°51'E
27	J4	**Hose**	Oromia	*North Shewa (R4)*	9°56'N 38°10'E
22	B2	**Hunde Lafto**	Oromia	*West Hararge*	9°7'N 40°58'E
30	E4	**Hurso**	Somali	*Siti*	9°36'N 41°38'E
17	I4	**Hurumu**	Oromia	*Ilubabor*	8°20'N 35°41'E

I

34	E2	**Ibnat**	Amhara	*South Gonder*	12°7'N 38°2'E
19	F2	**Ijaji**	Oromia	*West Shewa*	9°0'N 37°19'E
15	G5	**Imi**	Somali	*Shabelle*	6°28'N 42°10'E
17	I1	**Inango**	Oromia	*West Wellega*	9°9'N 35°41'E
20	A1	**Inchini**	Oromia	*West Shewa*	9°18'N 38°22'E
39	J1	**Inda Baguna**	Tigray	*North Western*	13°57'N 38°11'E
19	I4	**Indibir**	SNNPR	*Gurage*	8°7'N 37°55'E
28	D4	**Inewari**	Amhara	*North Shewa (R3)*	9°53'N 39°8'E
27	F2	**Inewend**	Amhara	*West Gojam*	10°23'N 37°12'E
33	I5	**Injibara**	Amhara	*Awi/Agew*	10°58'N 36°55'E
19	G2	**Irensa**	Oromia	*West Shewa*	8°58'N 37°34'E
16	C4	**Itang**	Gambella	*Agnuak*	8°12'N 34°16'E
20	E4	**Iteya**	Oromia	*Arsi*	8°8'N 39°14'E

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J

11	H2	**Jajura**	SNNPR	*Hadiya*	7°27'N 37°41'E
26	D3	**Jangir**	Oromia	*East Wellega*	10°4'N 36°40'E
14	A2	**Jara**	Oromia	*Bale*	7°27'N 40°48'E
34	D4	**Jara Gedo**	Amhara	*South Gonder*	11°23'N 37°52'E
26	E4	**Jardega**	Oromia	*Horo Guduru*	9°48'N 37°1'E
25	H5	**Jarso**	Oromia	*West Wellega*	9°27'N 35°19'E
4	D2	**Jelo**	SNNPR	*Segen Peoples'*	5°49'N 37°58'E
19	I5	**Jembero**	SNNPR	*Gurage*	8°1'N 38°2'E
27	I4	**Jemo Lefo**	Oromia	*West Shewa*	9°39'N 38°1'E
9	I4	**Jemu**	SNNPR	*Bench Maji*	6°38'N 35°46'E
29	G3	**Jewha**	Amhara	*Oromia*	10°6'N 39°58'E
27	G1	**Jiga**	Amhara	*West Gojam*	10°40'N 37°22'E
28	E3	**Jihur**	Amhara	*North Shewa (R3)*	10°0'N 39°14'E
23	I1	**Jijiga**	Somali	*Fafan*	9°20'N 42°47'E
16	B4	**Jikawo**	Gambella	*Nuer*	8°22'N 33°47'E
29	G2	**Jimate**	Amhara	*Oromia*	10°36'N 39°55'E
10	D1	**Jimma**	Oromia	*Jimma*	7°40'N 36°50'E
3	H3	**Jinka**	SNNPR	*South Omo*	5°47'N 36°33'E
18	A2	**Jogir**	Oromia	*West Wellega*	9°2'N 36°2'E

K

35	J5	**Kabe**	Amhara	*South Wollo*	10°49'N 39°28'E
27	H5	**Kachisi**	Oromia	*West Shewa*	9°35'N 37°50'E
3	H3	**Kaka**	SNNPR	*South Omo*	5°40'N 36°38'E
17	G2	**Kake**	Oromia	*Kelem Wellega*	8°55'N 35°3'E
29	G2	**Karakore**	Amhara	*North Shewa (R3)*	10°25'N 39°56'E
10	A2	**Kebechi**	SNNPR	*Kaffa*	7°27'N 36°6'E
20	A5	**Keber**	SNNPR	*Selti*	8°1'N 38°19'E
40	C4	**Kedamit**	Amhara	*Wag Himra*	12°52'N 38°51'E
17	J2	**Keki**	Oromia	*West Wellega*	9°4'N 35°49'E
4	D2	**Kele**	SNNPR	*Segen Peoples'*	5°50'N 37°53'E
28	D2	**Kelela**	Amhara	*South Wollo*	10°35'N 38°59'E
16	E1	**Kelem**	Oromia	*West Wellega*	9°9'N 34°31'E
13	F1	**Kelo**	Oromia	*Arsi*	7°43'N 39°33'E
26	C3	**Kelo**	Oromia	*East Wellega*	10°6'N 36°27'E
17	H2	**Kelo**	Oromia	*West Wellega*	8°55'N 35°21'E
4	A2	**Kemba**	SNNPR	*Gamo Gofa*	6°3'N 37°10'E
27	J5	**Kembolcha**	Oromia	*West Shewa*	9°30'N 38°12'E
29	G1	**Kemise**	Amhara	*Oromia*	10°42'N 39°51'E
18	B3	**Kemise**	Oromia	*Ilubabor*	8°28'N 36°10'E
10	B1	**Kemise**	Oromia	*Jimma*	7°47'N 36°21'E
34	D5	**Keraniya**	Amhara	*East Gojam*	10°58'N 37°58'E
5	F3	**Kercha**	Oromia	*Guji*	5°46'N 38°24'E
27	H4	**Kere Dobi**	Oromia	*West Shewa*	9°44'N 37°42'E
12	C2	**Kersa**	Oromia	*Arsi*	7°31'N 38°58'E
30	E5	**Kersa**	Oromia	*East Hararge*	9°27'N 41°52'E
33	J5	**Kesa**	Amhara	*Awi/Agew*	10°53'N 36°58'E
27	J5	**Ketket**	Oromia	*West Shewa*	9°22'N 38°12'E
18	C2	**Kewisa**	Oromia	*East Wellega*	8°56'N 36°28'E
27	G4	**Kewo**	Oromia	*Horo Guduru*	9°49'N 37°33'E
3	I3	**Key Afer**	SNNPR	*South Omo*	5°31'N 36°44'E
5	H2	**Kibre Mengist**	Oromia	*Guji*	5°53'N 38°59'E
33	H5	**Kidamaja**	Amhara	*Awi/Agew*	11°0'N 36°41'E
26	C1	**Kilaj**	Amhara	*Awi/Agew*	10°42'N 36°29'E
5	F3	**Kilenso**	Oromia	*Borena*	5°39'N 38°19'E
11	F4	**Kindo Halato**	SNNPR	*Wolayita*	6°45'N 37°20'E
26	E3	**Kiremu**	Oromia	*East Wellega*	9°57'N 36°52'E
24	E5	**Kober**	Oromia	*West Wellega*	9°28'N 34°33'E
36	A1	**Kobo**	Amhara	*North Wollo*	12°9'N 39°37'E
30	D5	**Kobo**	Oromia	*East Hararge*	9°22'N 41°28'E
5	F1	**Kofele**	Oromia	*Guji*	6°9'N 38°24'E
12	C3	**Kofele**	Oromia	*West Arsi*	7°4'N 38°47'E
20	D4	**Koka**	Oromia	*East Shewa*	8°26'N 39°1'E
35	I5	**Koke Ager**	Amhara	*South Wollo*	10°57'N 39°13'E
26	D4	**Kokofe**	Oromia	*East Wellega*	9°55'N 36°45'E
39	F5	**Kola Diba**	Amhara	*North Gonder*	12°25'N 37°20'E
4	A4	**Kolme**	SNNPR	*Segen Peoples'*	5°19'N 37°15'E
18	C2	**Kolobo**	Oromia	*East Wellega*	9°1'N 36°27'E
18	D4	**Koma**	Oromia	*Jimma*	8°27'N 36°51'E
36	B5	**Kombolcha**	Amhara	*South Wollo*	11°5'N 39°44'E
31	G5	**Kombolcha**	Oromia	*East Hararge*	9°26'N 42°7'E
27	G5	**Kombolcha**	Oromia	*Horo Guduru*	9°30'N 37°28'E
24	E2	**Komosh**	Benishangul Gumuz	*Asosa*	10°18'N 34°38'E
35	H3	**Kon**	Amhara	*North Wollo*	11°36'N 38°56'E
35	I3	**Kon Abo**	Amhara	*North Wollo*	11°45'N 39°9'E
20	B4	**Kondaltiti**	SNNPR	*Gurage*	8°24'N 38°37'E
18	B3	**Kone**	Oromia	*Ilubabor*	8°41'N 36°17'E
41	F5	**Korem**	Tigray	*Southern*	12°32'N 39°30'E
20	E1	**Koremas**	Amhara	*North Shewa (R3)*	9°13'N 39°17'E
26	B3	**Korka**	Benishangul Gumuz	*Metekel*	10°16'N 36°7'E
11	H5	**Kose**	SNNPR	*Gurage*	7°51'N 37°44'E
20	B5	**Koshe**	SNNPR	*Gurage*	8°0'N 38°31'E
4	E1	**Koti**	SNNPR	*Gedio*	6°17'N 38°13'E
18	D3	**Koye**	Oromia	*Jimma*	8°36'N 36°49'E
26	E2	**Kuch**	Amhara	*West Gojam*	10°24'N 37°2'E
21	F5	**Kula**	Oromia	*Arsi*	7°58'N 39°41'E
11	I2	**Kulito**	SNNPR	*Alaba*	7°19'N 38°6'E
35	I2	**Kulmesk**	Amhara	*North Wollo*	11°56'N 39°12'E
30	E5	**Kulubi**	Oromia	*East Hararge*	9°25'N 41°41'E
18	B4	**Kumbabe**	Oromia	*Ilubabor*	8°21'N 36°7'E
19	G4	**Kumbi**	Oromia	*Jimma*	8°7'N 37°29'E
33	J2	**Kunzila**	Amhara	*West Gojam*	11°52'N 37°1'E
28	D1	**Kurkura**	Amhara	*South Wollo*	10°44'N 39°13'E
24	D2	**Kurmuk**	Benishangul Gumuz	*Asosa*	10°33'N 34°17'E
36	A4	**Kuta Ber**	Amhara	*South Wollo*	11°16'N 39°32'E
12	B3	**Kuyera**	Oromia	*West Arsi*	7°14'N 38°39'E
27	I2	**Kuyi**	Amhara	*East Gojam*	10°30'N 37°59'E
41	F2	**Kwiha**	Tigray	*Southern*	13°28'N 39°32'E

L

35	H2	**Lalibela**	Amhara	*North Wollo*	12°2'N 39°2'E
16	B4	**Lare**	Gambella	*Agnuak*	8°20'N 33°57'E
3	H1	**Laska**	SNNPR	*Basketo*	6°18'N 36°36'E
31	J4	**Lefe Isa**	Somali	*Fafan*	9°37'N 42°59'E
22	C5	**Legehida**	Oromia	*Bale*	7°54'N 41°19'E
17	I5	**Leka**	Oromia	*Ilubabor*	8°5'N 35°40'E
12	A4	**Leku**	SNNPR	*Sidama*	6°52'N 38°26'E
20	B3	**Lemen**	Oromia	*South West Shewa*	8°36'N 38°36'E
28	C4	**Lemi**	Amhara	*North Shewa (R3)*	9°48'N 38°54'E
28	D2	**Ligwama**	Amhara	*South Wollo*	10°39'N 39°9'E
11	F4	**Loma Bale**	SNNPR	*Dawro*	6°54'N 37°13'E
37	G3	**Loqiya**	Afar	*Awsi (Zone 1)*	11°43'N 40°58'E
27	I3	**Lumame**	Amhara	*East Gojam*	10°15'N 37°56'E

M

38	C4	**Maganan**	Amhara	*North Gonder*	12°46'N 36°24'E
38	C4	**Maganan**	Amhara	*North Gonder*	12°47'N 36°25'E
40	C1	**Mahbere Tsige**	Tigray	*Central*	13°49'N 38°47'E
2	D1	**Maji**	SNNPR	*Bench Maji*	6°10'N 35°35'E
22	D3	**Majo Weldya**	Oromia	*East Hararge*	8°42'N 41°34'E
33	G4	**Mambuk**	Benishangul Gumuz	*Metekel*	11°17'N 36°14'E
33	G5	**Mandura**	Benishangul Gumuz	*Metekel*	11°5'N 36°25'E
27	F1	**Mankusa**	Amhara	*West Gojam*	10°41'N 37°10'E
32	D4	**Mankush**	Benishangul Gumuz	*Metekel*	11°19'N 35°34'E
9	H1	**Masha**	SNNPR	*Sheka*	7°44'N 35°28'E
41	F2	**May Keyah**	Tigray	*Southern*	13°19'N 39°31'E
41	F2	**May Mekdan**	Tigray	*Southern*	13°34'N 39°34'E
39	J2	**May Tsamri**	Tigray	*North Western*	13°34'N 38°11'E
41	F4	**Maychew**	Tigray	*Southern*	12°47'N 39°32'E
11	I3	**Mazoriya**	SNNPR	*Kembata Tembaro*	7°11'N 37°57'E
18	E4	**Mecha**	Oromia	*Jimma*	8°14'N 37°3'E
21	I3	**Mechara**	Oromia	*West Hararge*	8°36'N 40°20'E
11	G2	**Medula**	SNNPR	*Hadiya*	7°19'N 37°30'E
5	G3	**Megado**	Oromia	*Guji*	5°39'N 38°47'E
29	F2	**Mehal Meda**	Amhara	*North Shewa (R3)*	10°19'N 39°39'E
41	F4	**Mehoni**	Tigray	*Southern*	12°48'N 39°39'E
12	C5	**Mejo**	SNNPR	*Sidama*	6°22'N 38°57'E
34	E3	**Mekane Eyesus**	Amhara	*South Gonder*	11°36'N 38°3'E
28	C1	**Mekane Selam**	Amhara	*South Wollo*	10°44'N 38°45'E
40	E2	**MEKELE**	Tigray	*Southern*	13°29'N 39°28'E
17	I1	**Mekenejo**	Oromia	*West Wellega*	9°12'N 35°43'E

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20	C4	**Meki**	Oromia	*East Shewa*	8°9'N 38°49'E
18	A3	**Meko**	Oromia	*Ilubabor*	8°41'N 36°1'E
28	A5	**Mekoda**	Oromia	*West Shewa*	9°30'N 38°20'E
29	G1	**Mekoy**	Amhara	*Oromia*	10°42'N 39°47'E
39	G5	**Meksenyit**	Amhara	*North Gonder*	12°23'N 37°33'E
4	B2	**Mele**	SNNPR	*Gamo Gofa*	5°53'N 37°25'E
30	E4	**Melka Jeldu**	Dire Dawa	*Dire Dawa*	9°37'N 41°46'E
4	D3	**Melka Jewe**	SNNPR	*Segen Peoples'*	5°38'N 37°55'E
21	F2	**Melka Jilo**	Amhara	*North Shewa (R3)*	8°53'N 39°36'E
20	B3	**Melka Kunture**	Oromia	*South West Shewa*	8°42'N 38°36'E
31	G5	**Melka Rafu**	Oromia	*East Hararge*	9°28'N 42°11'E
21	H1	**Melka Sede**	Afar	*Gabi (Zone 3)*	9°15'N 40°8'E
21	H1	**Melka Werer**	Afar	*Gabi (Zone 3)*	9°20'N 40°10'E
20	E4	**Melkasa**	Oromia	*East Shewa*	8°24'N 39°20'E
13	G5	**Mena (Dolo Mena)**	Oromia	*Bale*	6°25'N 39°51'E
25	G4	**Mendi**	Oromia	*West Wellega*	9°48'N 35°6'E
28	E4	**Mendida**	Oromia	*North Shewa (R4)*	9°39'N 39°18'E
25	F2	**Menge**	Benishangul Gumuz	*Asosa*	10°21'N 34°45'E
28	D3	**Meranya**	Amhara	*North Shewa (R3)*	10°12'N 39°5'E
12	E2	**Meraro**	Oromia	*Arsi*	7°24'N 39°14'E
34	J4	**Merawi**	Amhara	*West Gojam*	11°24'N 37°9'E
10	E3	**Meri**	SNNPR	*Dawro*	7°2'N 37°6'E
36	B3	**Mersa**	Amhara	*North Wollo*	11°39'N 39°39'E
34	E5	**Mertule Maryam**	Amhara	*East Gojam*	10°51'N 38°16'E
22	C2	**Mesela**	Oromia	*West Hararge*	9°5'N 41°10'E
39	G2	**Mesfinto**	Tigray	*Western*	13°29'N 37°22'E
34	B3	**Meshenti**	Amhara	*West Gojam*	11°28'N 37°16'E
21	F1	**Meteh Bila**	Amhara	*North Shewa (R3)*	9°12'N 39°42'E
21	G2	**Metehara**	Oromia	*East Shewa*	8°54'N 39°54'E
38	B3	**Metema**	Amhara	*North Gonder*	12°56'N 36°10'E
10	D2	**Metoso**	Oromia	*Jimma*	7°25'N 36°52'E
17	I4	**Metu (Mettu)**	Oromia	*Ilubabor*	8°18'N 35°35'E
29	G3	**Mezezo**	Amhara	*North Shewa (R3)*	10°0'N 39°44'E
21	I3	**Micheta**	Oromia	*Arsi*	8°33'N 40°18'E
28	D3	**Mida**	Amhara	*North Shewa (R3)*	10°18'N 39°8'E
22	A1	**Mieso**	Oromia	*West Hararge*	9°13'N 40°45'E
37	F4	**Mile**	Afar	*Awsi (Zone 1)*	11°25'N 40°45'E
27	J5	**Minare**	Oromia	*West Shewa*	9°36'N 38°16'E
9	I3	**Mizan Teferi**	SNNPR	*Bench Maji*	7°00'N 35°25'E
20	D3	**Modjo**	Oromia	*East Shewa*	8°35'N 39°7'E
29	F3	**Molale**	Amhara	*North Shewa (R3)*	10°7'N 39°40'E
11	F5	**Morka**	SNNPR	*Gamo Gofa*	6°25'N 37°18'E
11	H1	**Morsito**	SNNPR	*Hadiya*	7°42'N 37°49'E
34	D5	**Mota**	Amhara	*East Gojam*	11°4'N 37°52'E
18	E2	**Mote**	Oromia	*East Wellega*	8°49'N 36°54'E
5	J4	**Mugayo**	Oromia	*Guji*	5°12'N 39°25'E
28	B5	**Muger**	Oromia	*West Shewa*	9°28'N 38°36'E
16	E3	**Mugi**	Oromia	*Kelem Wellega*	8°34'N 34°36'E
35	I2	**Muja**	Amhara	*North Wollo*	12°0'N 39°17'E
28	C5	**Muke Turi**	Oromia	*North Shewa (R4)*	9°33'N 38°52'E
17	I1	**Muklemi**	Oromia	*West Wellega*	9°17'N 35°32'E
28	B5	**Mulo**	Oromia	*North Shewa (R4)*	9°22'N 38°39'E
12	C2	**Munesa**	Oromia	*Arsi*	7°34'N 38°54'E

N

11	F2	**Nada**	Oromia	*Jimma*	7°37'N 37°14'E
19	G5	**Natri**	Oromia	*Jimma*	8°2'N 37°27'E
35	F3	**Nefas Mewcha**	Amhara	*South Gonder*	11°43'N 38°28'E
6	A4	**Negele**	Oromia	*Guji*	5°20'N 39°34'E
25	H5	**Nejo**	Oromia	*West Wellega*	9°30'N 35°30'E
18	C2	**Nekemte**	Oromia	*East Wellega*	9°5'N 36°34'E
17	I4	**Nopa**	Oromia	*Ilubabor*	8°23'N 35°36'E
24	E5	**Nopa**	Oromia	*West Wellega*	9°30'N 34°38'E
18	D3	**Nunu**	Oromia	*East Wellega*	8°45'N 36°38'E

O

26	E3	**Obera**	Oromia	*Horo Guduru*	10°0'N 37°1'E
20	D5	**Ogokho**	Oromia	*Arsi*	8°3'N 38°59'E
20	C4	**Ombole**	Oromia	*East Shewa*	8°22'N 38°46'E
32	C2	**Omedila**	Amhara	*North Gonder*	11°55'N 35°16'E
3	F5	**Omorate**	SNNPR	*South Omo*	4°48'N 36°3'E
3	J1	**Otolo**	SNNPR	*Gamo Gofa*	6°10'N 37°6'E

P

33	G4	**Pawe**	Benishangul Gumuz	*Metekel*	11°14'N 36°16'E

R

29	F2	**Rabel**	Amhara	*North Shewa (R3)*	10°29'N 39°39'E
28	C3	**Rema**	Amhara	*North Shewa (R3)*	10°15'N 38°54'E
13	F4	**Rira**	Oromia	*Bale*	6°46'N 39°44'E
19	H2	**Rob Geba**	Oromia	*West Shewa*	9°7'N 37°38'E
27	H2	**Rob Gebeya**	Amhara	*East Gojam*	10°32'N 37°45'E
18	E1	**Rob Gebeya**	Oromia	*East Wellega*	9°9'N 36°55'E
17	F3	**Rob Gebeya**	Oromia	*Kelem Wellega*	8°41'N 34°52'E
13	H3	**Robe**	Oromia	*Bale*	7°7'N 40°0'E
21	F5	**Robi**	Oromia	*Arsi*	7°51'N 39°37'E
34	B1	**Robit**	Amhara	*North Gonder*	12°18'N 37°23'E
36	A2	**Robit**	Amhara	*North Wollo*	12°0'N 39°37'E
11	I3	**Ropi**	Oromia	*West Arsi*	7°9'N 38°6'E
12	D1	**Sagure**	Oromia	*Arsi*	7°44'N 39°9'E

S

40	D3	**Samre**	Tigray	*Southern*	13°11'N 39°12'E
39	I3	**Sankaber**	Amhara	*North Gonder*	13°13'N 38°2'E
29	F4	**Sasit**	Amhara	*North Shewa (R3)*	9°55'N 39°29'E
3	I1	**Sawla**	SNNPR	*Gamo Gofa*	6°17'N 36°52'E
20	B2	**Sebeta**	Oromia	*South West Shewa*	8°54'N 38°36'E
34	D5	**Sede**	Amhara	*East Gojam*	10°55'N 37°53'E
13	G2	**Sede**	Oromia	*Arsi*	7°32'N 39°58'E
16	E3	**Sedi (Ashi)**	Oromia	*Kelem Wellega*	8°39'N 34°40'E
13	G2	**Sedika**	Oromia	*Arsi*	7°37'N 39°48'E
15	I1	**Segeg**	Somali	*Nogob*	7°41'N 42°50'E
4	B3	**Segen**	SNNPR	*Segen Peoples'*	5°35'N 37°32'E
35	J3	**Segora**	Amhara	*South Wollo*	11°34'N 39°20'E
10	D2	**Seka**	Oromia	*Jimma*	7°36'N 36°43'E
18	E4	**Seka**	Oromia	*Jimma*	8°12'N 36°56'E
19	G5	**Sekoru**	Oromia	*Jimma*	7°55'N 37°25'E
40	D4	**Sekota**	Amhara	*Wag Himra*	12°37'N 39°1'E
29	F4	**Sela Dingay**	Amhara	*North Shewa (R3)*	9°57'N 39°37'E
11	G5	**Selam Ber**	SNNPR	*Gamo Gofa*	6°28'N 37°27'E
13	H3	**Selka**	Oromia	*Bale*	7°2'N 40°12'E
10	D2	**Sembo**	Oromia	*Jimma*	7°34'N 36°37'E
37	G3	**SEMERA**	Afar	*Awsi (Zone 1)*	11°47'N 41°0'E
29	G3	**Senbete**	Amhara	*Oromia*	10°18'N 39°59'E
20	D2	**Sendafa**	Oromia	*North Shewa (R4)*	9°9'N 39°1'E
41	F1	**Senkata (Negash)**	Tigray	*Eastern*	13°53'N 39°36'E
27	H2	**Senyin**	Amhara	*East Gojam*	10°35'N 37°41'E
10	D1	**Senyo Gebeya**	Oromia	*Jimma*	7°43'N 36°37'E
38	E5	**Seraba**	Amhara	*North Gonder*	12°33'N 37°04'E
10	E1	**Serbo**	Oromia	*Jimma*	7°42'N 36°59'E
13	H1	**Seru**	Oromia	*Arsi*	7°40'N 40°12'E
18	B5	**Setema**	Oromia	*Jimma*	8°2'N 36°20'E
19	F3	**Seyo**	Oromia	*West Shewa*	8°46'N 37°15'E
5	H3	**Shakiso**	Oromia	*Guji*	5°46'N 38°53'E
26	E5	**Shambu**	Oromia	*Horo Guduru*	9°33'N 37°5'E
12	B3	**Shashemene**	Oromia	*West Arsi*	7°11'N 38°35'E
10	C2	**Shebe**	Oromia	*Jimma*	7°31'N 36°31'E
16	E3	**Shebel**	Oromia	*Kelem Wellega*	8°28'N 34°35'E
19	F2	**Sheboka**	Oromia	*West Shewa*	9°5'N 37°7'E
41	F2	**Shehet**	Afar	*Kilbati (Zone 2)*	13°21'N 39°45'E
14	A1	**Sheki Husen**	Oromia	*Bale*	7°44'N 40°42'E
27	G2	**Shelel**	Amhara	*East Gojam*	10°34'N 37°35'E
19	G3	**Shenen**	Oromia	*West Shewa*	8°44'N 37°27'E
20	E5	**Sheno**	Oromia	*North Shewa (R4)*	9°19'N 39°17'E
9	I3	**Shewa Gimira**	SNNPR	*Bench Maji*	6°57'N 35°46'E
29	G3	**Shewa Robit**	Amhara	*North Shewa (R3)*	10°0'N 39°54'E
27	I5	**Shikute**	Oromia	*West Shewa*	9°22'N 38°1'E
28	D2	**Shil Afaf**	Amhara	*South Wollo*	10°22'N 39°10'E
26	E1	**Shindi**	Amhara	*West Gojam*	10°39'N 36°57'E
31	F4	**Shinile**	Somali	*Siti*	9°49'N 41°52'E
20	A1	**Shino**	Oromia	*West Shewa*	9°19'N 38°16'E
12	D3	**Shire**	Oromia	*West Arsi*	7°14'N 38°59'E
20	E1	**Shola Gebeya**	Amhara	*North Shewa (R3)*	9°12'N 39°24'E
11	I3	**Shone**	SNNPR	*Hadiya*	7°8'N 37°57'E
17	G4	**Sibo**	Oromia	*Ilubabor*	8°14'N 35°14'E
17	G2	**Sichawo**	Oromia	*Kelem Wellega*	9°6'N 35°1'E

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18	A5	**Sigamo**	Oromia	*Jimma*	7°54'N 36°5'E
19	G3	**Silk Amba**	Oromia	*West Shewa*	8°32'N 37°25'E
12	E2	**Siltana**	Oromia	*Arsi*	7°23'N 39°23'E
18	C4	**Sineso**	Oromia	*Ilubabor*	8°8'N 36°33'E
20	E4	**Sire**	Oromia	*Arsi*	8°16'N 39°29'E
18	D2	**Sire**	Oromia	*East Wellega*	9°2'N 36°52'E
36	A3	**Sirinka**	Amhara	*North Wollo*	11°45'N 39°36'E
40	C4	**Siska**	Amhara	*Wag Himra*	12°45'N 38°48'E
5	G3	**Soda**	Oromia	*Borena*	5°29'N 38°36'E
11	H4	**Soddo**	SNNPR	*Wolayita*	6°51'N 37°45'E
20	E4	**Sodere**	Oromia	*East Shewa*	8°24'N 39°22'E
5	G2	**Solemo**	Oromia	*Guji*	6°6'N 38°35'E
26	E4	**Sombo**	Oromia	*Horo Guduru*	9°44'N 37°1'E
10	D3	**Soyema**	SNNPR	*Konta*	7°16'N 36°49'E
4	D3	**Soyema**	SNNPR	*Segen Peoples'*	5°29'N 37°51'E
36	B4	**Sulula**	Amhara	*South Wollo*	11°14'N 39°41'E
20	C1	**Sululta**	Oromia	*North Shewa (R4)*	9°10'N 38°45'E
17	I3	**Supe**	Oromia	*Ilubabor*	8°31'N 35°39'E
26	B4	**Surge**	Oromia	*East Wellega*	9°56'N 36°10'E
4	E5	**Surupa**	Oromia	*Borena*	5°8'N 38°18'E

T

27	H1	**Tame**	Amhara	*West Gojam*	10°46'N 37°38'E
29	F4	**Tarmaber**	Amhara	*North Shewa (R3)*	9°49'N 39°43'E
19	H4	**Tawula**	SNNPR	*Gurage*	8°16'N 37°41'E
11	H4	**Tebela**	SNNPR	*Wolayita*	6°42'N 37°46'E
19	G4	**Tedele**	SNNPR	*Gurage*	8°18'N 37°37'E
4	E5	**Tedim**	Oromia	*Borena*	5°1'N 38°9'E
12	A5	**Teferi Kela**	SNNPR	*Sidama*	6°29'N 38°23'E
20	B2	**Tefki**	Oromia	*South West Shewa*	8°50'N 38°29'E
4	B5	**Teltele**	Oromia	*Borena*	5°3'N 37°22'E
9	I3	**Temenja Yazhi**	SNNPR	*Bench Maji*	7°4'N 35°38'E
37	G3	**Tendaho**	Afar	*Awsi (Zone 1)*	11°41'N 40°56'E
35	I4	**Tenta**	Amhara	*South Wollo*	11°19'N 39°15'E
9	H2	**Tepi**	Gambella	*Majang*	7°12'N 35°25'E
32	E1	**Tewodros Ketema**	Amhara	*North Gonder*	12°13'N 35°53'E
17	F2	**Tibe**	Oromia	*Kelem Wellega*	8°58'N 34°45'E
19	F2	**Tibe**	Oromia	*West Shewa*	9°4'N 37°11'E
13	F1	**Ticho**	Oromia	*Arsi*	7°48'N 39°30'E
39	F3	**Tikil Dingay**	Amhara	*North Gonder*	12°44'N 37°24'E
33	J5	**Tilili**	Amhara	*Awi/Agew*	10°51'N 37°1'E
21	I4	**Timuga**	Oromia	*Arsi*	8°25'N 40°14'E
19	F5	**Tiro**	Oromia	*Jimma*	8°4'N 37°12'E
34	C3	**Tis Abay**	Amhara	*West Gojam*	11°29'N 37°34'E
20	B4	**Tiya**	SNNPR	*Gurage*	8°26'N 38°36'E
18	C5	**Toba**	Oromia	*Jimma*	8°0'N 36°29'E
25	G4	**Toba**	Oromia	*West Wellega*	9°41'N 35°15'E
11	G1	**Toba**	SNNPR	*Yem*	7°44'N 37°28'E
16	E1	**Tobi**	Oromia	*West Wellega*	9°15'N 34°34'E
10	E3	**Tocha**	SNNPR	*Dawro*	7°5'N 37°1'E
11	F3	**Tocha Sodo**	SNNPR	*Dawro*	7°8'N 37°9'E
19	F4	**Toley**	Oromia	*Jimma*	8°17'N 37°22'E
2	H5	**Toom**	SNNPR	*Bench Maji*	6°18'N 35°24'E
12	A1	**Tora**	SNNPR	*Selti*	7°51'N 38°25'E
4	E2	**Tore**	Oromia	*Borena*	5°55'N 38°9'E
12	B4	**Tula**	SNNPR	*Sidama*	6°57'N 38°28'E
18	B3	**Tulema**	Oromia	*Ilubabor*	8°45'N 36°11'E
11	F3	**Tulema**	SNNPR	*Dawro*	7°0'N 37°14'E
19	J3	**Tulu Bolo**	Oromia	*South West Shewa*	8°39'N 38°12'E
28	J4	**Tulu Miki**	Oromia	*North Shewa (R4)*	9°54'N 38°20'E
3	H5	**Turmi**	SNNPR	*South Omo*	4°48'N 36°29'E

U

17	H4	**Uka**	Oromia	*Ilubabor*	8°10'N 35°21'E
18	D4	**Ulawarta**	Oromia	*Jimma*	8°20'N 36°51'E

W

4	B1	**Wacha**	SNNPR	*Gamo Gofa*	6°19'N 37°18'E
9	I3	**Wacha**	SNNPR	*Kaffa*	7°7'N 35°47'E
5	I3	**Wadera**	Oromia	*Guji*	5°46'N 39°18'E
36	A1	**Waja**	Tigray	*Southern*	12°17'N 39°36'E
11	H5	**Wajifo**	SNNPR	*Gamo Gofa*	6°27'N 37°44'E
11	F3	**Waka**	SNNPR	*Dawro*	7°3'N 37°10'E
18	D3	**Wama Adere**	Oromia	*East Wellega*	8°45'N 36°45'E
34	C3	**Wanzaye**	Amhara	*South Gonder*	11°46'N 37°41'E
30	E5	**Water**	Oromia	*East Hararge*	9°22'N 41°46'E
28	D4	**Weberi**	Oromia	*North Shewa (R4)*	9°40'N 39°1'E
27	I2	**Webrje**	Amhara	*East Gojam*	10°23'N 38°3'E
35	I3	**Wegel Tena**	Amhara	*North Wollo*	11°35'N 39°13'E
28	C2	**Wegeti**	Amhara	*South Wollo*	10°35'N 38°45'E
38	D4	**Wehini**	Amhara	*North Gonder*	12°37'N 36°39'E
39	H3	**Wekin**	Amhara	*North Gonder*	13°3'N 37°49'E
11	F3	**Welde Hane**	SNNPR	*Dawro*	7°14'N 37°16'E
36	A2	**Weldiya**	Amhara	*North Wollo*	11°49'N 39°36'E
20	E3	**Welenchiti**	Oromia	*East Shewa*	8°39'N 39°25'E
28	B5	**Welenkombi**	Oromia	*West Shewa*	9°24'N 38°29'E
19	I3	**Weliso**	Oromia	*South West Shewa*	8°32'N 37°58'E
19	H4	**Welkite**	SNNPR	*Gurage*	8°16'N 37°46'E
4	E1	**Wenago**	SNNPR	*Gedio*	6°18'N 38°15'E
12	B3	**Wendo Genet**	SNNPR	*Sidama*	7°2'N 38°36'E
20	D4	**Wenji**	Oromia	*East Shewa*	8°27'N 39°13'E
20	D1	**Wenoda**	Oromia	*North Shewa (R4)*	9°17'N 39°5'E
28	E2	**Were Ilu**	Amhara	*South Wollo*	10°35'N 39°26'E
28	B2	**Werk Amba**	Amhara	*South Wollo*	10°38'N 38°34'E
40	D1	**Werk Amba**	Tigray	*Central*	13°44'N 39°00'E
12	D4	**Werka**	Oromia	*West Arsi*	6°43'N 39°10'E
33	J4	**Wetet Abay**	Amhara	*West Gojam*	11°22'N 37°2'E
41	G5	**Weyra Wuha**	Tigray	*Southern*	12°32'N 39°46'E
3	H2	**Wib Hamer**	SNNPR	*South Omo*	6°3'N 36°35'E
36	A3	**Wichale**	Amhara	*South Wollo*	11°31'N 39°36'E
12	B4	**Wijigra**	SNNPR	*Sidama*	6°56'N 38°33'E
36	A3	**Wirgesa**	Amhara	*North Wollo*	11°32'N 39°37'E
10	E4	**Wishaye Bele**	SNNPR	*Dawro*	6°54'N 37°0'E
3	J4	**Woito**	SNNPR	*South Omo*	5°22'N 36°59'E
20	E5	**Wolonkomi**	Oromia	*Arsi*	8°2'N 39°15'E
34	C2	**Woreta**	Amhara	*South Gonder*	11°55'N 37°41'E
41	F1	**Wukro**	Tigray	*Eastern*	13°46'N 39°35'E
10	B2	**Wushwush**	SNNPR	*Kaffa*	7°18'N 36°8'E

Y

4	E5	**Yabelo**	Oromia	*Borena*	4°53'N 38°5'E
18	C4	**Yanfa**	Oromia	*Ilubabor*	8°14'N 36°35'E
17	H2	**Yara**	Oromia	*West Wellega*	9°5'N 35°23'E
17	J4	**Yayu**	Oromia	*Ilubabor*	8°20'N 35°49'E
27	H2	**Yebokile**	Amhara	*East Gojam*	10°25'N 37°51'E
10	D1	**Yebu**	Oromia	*Jimma*	7°47'N 36°43'E
40	D3	**Yechilay**	Tigray	*Central*	13°17'N 38°59'E
27	H3	**Yejube**	Amhara	*East Gojam*	10°8'N 37°44'E
27	J3	**Yekoza**	Amhara	*East Gojam*	10°14'N 38°12'E
18	C4	**Yembero**	Oromia	*Ilubabor*	8°10'N 36°27'E
27	J2	**Yetmen**	Amhara	*East Gojam*	10°20'N 38°8'E
27	G2	**Yewla**	Amhara	*East Gojam*	10°24'N 37°34'E
34	C2	**Yifag**	Amhara	*South Gonder*	12°4'N 37°44'E
5	G1	**Yirba Moda**	Oromia	*Guji*	6°12'N 38°42'E
12	A4	**Yirga Alem**	SNNPR	*Sidama*	6°44'N 38°24'E
4	E1	**Yirgacheffe**	SNNPR	*Gedio*	6°9'N 38°12'E
33	I3	**Yismala**	Amhara	*West Gojam*	11°36'N 36°54'E
17	H2	**Yubdo**	Oromia	*West Wellega*	8°57'N 35°26'E

Z

39	I2	**Zarima**	Amhara	*North Gonder*	13°20'N 37°53'E
11	H5	**Zefine**	SNNPR	*Gamo Gofa*	6°28'N 37°38'E
34	B3	**Zege (Zeghie)**	Amhara	*West Gojam*	11°41'N 37°19'E
5	I2	**Zembaba Wiha**	Oromia	*Guji*	5°53'N 39°10'E
26	B1	**Zigin**	Benishangul Gumuz	*Metekel*	10°40'N 36°9'E
20	B5	**Ziway**	Oromia	*East Shewa*	7°55'N 38°42'E

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ECFF
Environment & Coffee Forest Forum

Ethiopia is the birth-place of coffee, the home of Wild Arabica coffee (*Coffea arabica*) and the largest coffee producer in Africa. Ethiopian coffee is world-renowned for its wide diversity of flavour profiles, including the celebrated coffees of Gesha, Harar, Limu, Sidamo, and Yirgacheffe. Coffee farming in Ethiopia is intimately associated with forest, and coffee-drinking is an important part of Ethiopian culture and society.

The *Coffee Atlas of Ethiopia* maps the coffee landscape of Ethiopia, showing where coffee is (and could be) farmed, and the location of wild Arabica coffee forests. The maps include the main coffee-growing origins, coffee towns and coffee delivery centres, as well as other useful features. The Atlas maps are accompanied by introductory text on geography, coffee use and consumption, botany, the coffee-growing climate and environment, coffee farming, harvesting and processing, and an overview of the main coffee areas. The *Coffee Atlas of Ethiopia* is an essential resource for anyone working with, or interested in, coffee, and serves as a key reference for the natural landscape of Ethiopia.

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Pages: 16 + 10

Package 'rCAT'

January 17, 2017

Title Conservation Assessment Tools

Version 0.1.5

Date 2017-01-11

Description A set of tools to help with species conservation assessments (Red List threat assessments). Includes tool for Extent of occurrence, Area of Occupancy, Minimum Enclosing Rectangle, a geographic Projection Wizard and Species batch processing.

Depends R (>= 3.3.0)

Suggests rgeos, rgbif (>= 0.9.2), downscale (>= 1.2-4), knitr, rmarkdown, R.rsp

License GPL-2

Imports pracma (>= 1.9.5), rgdal (>= 1.2-5), sp (>= 1.2-3), grDevices (>= 3.3.2)

Encoding UTF-8

LazyData true

RoxygenNote 5.0.1

VignetteBuilder R.rsp

NeedsCompilation no

Author Justin Moat [aut, cre], Steven Bachman [ctb]

Maintainer Justin Moat <J.Moat@kew.org>

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`AOORating` *IUCN rating based from AOO Area*

Description

Calculates IUCN rating based on Area of occupancy (AOO) Area in km2

Usage

```
AOORating(AOOArea, abb)
```

Arguments

`AOOArea`	Area in km2
`abb`	TRUE or FALSE , TRUE = 2 letter code, FALSE = full text (see value), default = TRUE

Value

Text one of CR, EN, VU, NT, LC or Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern

Note

Any negative values are assumpted to be positive. Near Threatened is set at 3,000 km2, follow example in IUCN Guidelines version 11. 2014

Author(s)

Justin Moat. J.Moat@kew.org

References

Bachman, S., Moat, J., Hill, A.W., de Torre, J., Scott, B., 2011. Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. Zookeys 126, 117–26. doi:10.3897/zookeys.150.2109

Moat, J., Bachman, S., n.d. GeoCAT Geospatial Conservation Assessment Tool [WWW Document]. URL http://geocat.kew.org/

IUCN, 2012. IUCN Red List Categories and Criteria, 2nd ed. IUCN, Gland, Switzerland.

IUCN Standards and Petitions Subcommittee, 2014. Guidelines for Using the IUCN Red List Categories and Criteria. Version 11.

IUCN Standards and Petitions Subcommittee, 2016. Guidelines for Using the IUCN Red List Categories and Criteria. Version 12.

Joppa, L.N., Butchart, S.H.M., Hoffmann, M., Bachman, S.P., Akçakaya, H.R., Moat, J.F., Böhm, M., Holland, R.A., Newton, A., Polidoro, B., Hughes, A., 2016. Impact of alternative metrics on estimates of extent of occurrence for extinction risk assessment. Conserv. Biol. 30, 362–370. doi:10.1111/cobi.12591

See Also

AOOsimp for AOO calculations

Examples

```
AOOArea <- 25
AOORtext <- EOORating(AOOArea,FALSE)
```

AOOsimp *Area of Occupancy (AOO)*

Description

Calculates the number of ocupied cells for Area of Occupancy from a set of points (x,y), usually in metres, with orgin 0,0

Usage

```
AOOsimp(thepoints, cellsize)
```

Arguments

thepoints	set of points in metres i.e. c(x,y)
cellsize	size of cell (length) in metres

Details

calculates a very simple AOO area from a set of points

Value

integer number of unique cells as an integer

Author(s)

Justin Moat. J.Moat@kew.org

References

Bachman, S., Moat, J., Hill, A.W., de Torre, J., Scott, B., 2011. Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. Zookeys 126, 117–26. doi:10.3897/zookeys.150.2109

Moat, J., Bachman, S., n.d. GeoCAT Geospatial Conservation Assessment Tool. URL http://geocat.kew.org/

See Also

AOORating for AOO Ratings,

Examples

```
x <- runif (20,0,10)
y <- runif (20,0,10)
df <- data.frame(x,y)
AOOsimp (df,2)
```

---

cart2ll *Cartesian (x,y,z) to Geographic coordinates*

Description

calculates the latitude and longtitude cordinates in radians from Cartesian coordinates (x,y,z)

Usage

```
cart2ll(x, y, z)
```

Arguments

x	East to West coordinate in metres
y	South to North coordinate in metres
z	height coordinate in metres

Value

dataframe of latitude,longtitude

Author(s)

Justin Moat. J.Moat@kew.org

ConBatch *Batch process, preliminary conservation assessments*

Description

Combines all of routines in rCAT to process multiple species for AOO, EOO etc.

Usage

```
ConBatch(taxa, lat, long, cellsize, project2gether)
```

Arguments

taxa	field which defines a list of species or taxa
lat	field which defines the latitude set of points
long	field which defines the longtitude set of points
cellsize	cell length in metres used to for AOO projection N.B. IUCN recommend 2000 m (ie 2 km)
project2gether	TRUE or FALSE, TRUE all data is projected together using the centre of all latitudes and longtitudes. FALSE each species is projected separately. Default = FALSE

Details

This function expects a list of taxa and latitudes and longitudes.ie

species_w	85.388000	84.33100
species_w	-45.467000	88.41500
species_w	-34.339000	-149.52600
species_x	-29.620000	79.11900
species_x	33.409000	-33.94700
species_x	64.692000	-149.18900
species_y	2.308000	-140.21900
species_y	41.452000	-3.65600
species_y	-30.475000	-129.99600

etc

Value

dataframe with; taxa ,Number of points, Area of the enclosing recetangle, EOO Area in km2, AOO area in km2, EOO IUCN category, AOO IUCN category

	taxa	NOP	MER	EOOkm2	AOO2km	EOOcat	AOOcat
1	species x	14	918562.259811711	585915.607417865	14	LC	EN
2	species y	124	1717224.64389286	634149.482670821	124	LC	EN
3	species z	61	22622717.2314339	17839113.1220552	61	LC	EN
4	species w	1130	509390660.388499	506445176.073246	1130	LC	VU

Note

Has a switch to either project all data as a whole or each taxa separately. I would suggest you use this switch if data is all from a simlar area (i.e. all from one country/region)

Author(s)

Justin Moat. J.Moat@kew.org

References

Bachman, S., Moat, J., Hill, A.W., de Torre, J., Scott, B., 2011. Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. Zookeys 126, 117–26. doi:10.3897/zookeys.150.2109

Moat, J. F. 2007. Conservation assessment tools extension for ArcView 3.x, version 1.2. Retrieved from http://www.kew.org/gis/projects/cats/catsdoc.pdf

Moat, J., Bachman, S.,(2017) GeoCAT Geospatial Conservation Assessment Tool [WWW Document]. URL http://geocat.kew.org/

Joppa, L.N., Butchart, S.H.M., Hoffmann, M., Bachman, S.P., Akçakaya, H.R., Moat, J.F., Böhm, M., Holland, R.A., Newton, A., Polidoro, B., Hughes, A., 2016. Impact of alternative metrics on estimates of extent of occurrence for extinction risk assessment. Conserv. Biol. 30, 362–370. doi:10.1111/cobi.12591

See Also

`MER` for Minimum Enclosing Rectangle calculations, `EOOarea` for EOO calculations, `EOORating` for EOO Ratings, `AOOsimp` for AOO calculations, `AOORating` for AOO Ratings,

Examples

```
mydata <- read.csv(system.file("extdata","multiple_species.csv",package="rCAT"))
resultdf <- ConBatch(mydata$scientificname,mydata$latitude,mydata$longitude,2000,FALSE)
```

deg2rad *Degrees to radians*

Description

Calculates radians from degrees or degrees from radians

Usage

```
deg2rad(deg)
```

Arguments

deg	number in degrees

Value

number

Author(s)

Justin Moat. J.Moat@kew.org

Examples

```
a <- 30
deg2rad(a)
```

EOOarea *Extent of Occurance (EOO) Area*

Description

Calculates the Extent of Occurance from a set of points (x,y)

Usage

```
EOOarea(thepoints)
```

Arguments

thepoints	dataframe of points i.e. c(x,y)

Details

calculates the EOO area of a set of popints'

Value

float_value area of EOO polygon

Note

area returned is in x,y units, but negative as polygon is constructed anticlockwise

Author(s)

Justin Moat. J.Moat@kew.org

References

Bachman, S., Moat, J., Hill, A.W., de Torre, J., Scott, B., 2011. Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. Zookeys 126, 117–26. doi:10.3897/zookeys.150.2109

Moat, J., Bachman, S., n.d. GeoCAT Geospatial Conservation Assessment Tool [WWW Document]. URL http://geocat.kew.org/

Joppa, L.N., Butchart, S.H.M., Hoffmann, M., Bachman, S.P., Akçakaya, H.R., Moat, J.F., Böhm, M., Holland, R.A., Newton, A., Polidoro, B., Hughes, A., 2016. Impact of alternative metrics on estimates of extent of occurrence for extinction risk assessment. Conserv. Biol. 30, 362–370. doi:10.1111/cobi.12591

See Also

EOORating for EOO Ratings

Examples

```
x <- runif (20,0,10)
y <- runif (20,0,10)
df <- data.frame(x,y)
EOOarea (df)
```

EOORating *IUCN rating based from EOO Area*

Description

Calculates IUCN rating based on Extent of Occurance (EOO) Area in km2

Usage

```
EOORating(EOOArea, abb)
```

Arguments

EOOArea	Area in km2
abb	TRUE or FALSE , TRUE = 2 letter code, FALSE = full text (see value), default = TRUE

Details

Calculates IUCN rating from EOO

Value

Text one of CR, EN, VU, NT, LC or Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern

Note

Any negative values are assumpted to be positive. Near Threatened is set at 30,000 km2, follow example in IUCN petition 2014

Author(s)

Justin Moat. J.Moat@kew.org

References

Bachman, S., Moat, J., Hill, A.W., de Torre, J., Scott, B., 2011. Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. Zookeys 126, 117–26. doi:10.3897/zookeys.150.2109

Moat, J., Bachman, S., n.d. GeoCAT Geospatial Conservation Assessment Tool [WWW Document]. URL http://geocat.kew.org/

IUCN, 2012. IUCN RED LIST CATEGORIES AND CRITERIA, 2nd ed. IUCN, Gland, Switzerland.

IUCN Standards and Petitions Subcommittee, 2014. Guidelines for Using the IUCN Red List Categories and Criteria. Version 11.

IUCN Standards and Petitions Subcommittee, 2016. Guidelines for Using the IUCN Red List Categories and Criteria. Version 12.

Joppa, L.N., Butchart, S.H.M., Hoffmann, M., Bachman, S.P., Akçakaya, H.R., Moat, J.F., Böhm, M., Holland, R.A., Newton, A., Polidoro, B., Hughes, A., 2016. Impact of alternative metrics on estimates of extent of occurrence for extinction risk assessment. Conserv. Biol. 30, 362–370. doi:10.1111/cobi.12591

See Also

EOOarea for EOO calculations

Examples

```
EOOArea <- 25
EOORtext <- EOORating(EOOArea,TRUE)
```

ll2cart *Geographic coordinates to cartesian (x,y,z)*

Description

Calculates the Cartesian cordinates (x,y,z) from lat long in radians

Usage

```
ll2cart(latr, longr)
```

Arguments

latr	latitude point in radians
longr	longtitude point in radians

Value

dataframe of x,y,z

Author(s)

Justin Moat. J.Moat@kew.org

References

Descartes, R., 1637. Discours de la methode. A Leyde, De l'imprimerie de I. Maire, Paris.

Examples

```
lat <- runif (200,-24,-12)
long <- runif (200,43,51)
thepoints <- data.frame(lat,long)
llrad <- deg2rad(thepoints)
cartp <- ll2cart(llrad$lat,llrad$long)
```

MER *Minimum Enclosing Rectangle (MER)*

Description

Calculates the minimum enclosing rectangle (MER) from a set of points (x,y)

Usage

```
MER(thepoints)
```

Arguments

thepoints	dataframe of points ie c(x,y)

Details

calculates the MER of a set of numbers'

Value

list of 4 doubles = xmin,xmax,ymin,ymax

Author(s)

Justin Moat. J.Moat@kew.org

Examples

```
x <- runif (20,0,10)
y <- runif (20,0,10)
df <- data.frame(x,y)
MER (df)
```

Mode *Mode of a test of points*

Description

Calculates the mode (the value that occurs most often) of a set of data - note the capital M

Usage

```
Mode(x)
```

Arguments

x	set of numbers

Details

calculates the mode of a set of numbers'

Value

number

Note

Orginally from http://stackoverflow.com/questions/2547402/standard-library-function-in-r-for-finding-the-mode

Author(s)

Justin Moat. J.Moat@kew.org

Examples

```
a <- c(5,5,5,6,7,8,9)
Mode(a)
```

---

pro2sph *Cartesian coordinate projection*

Description

calculates Cartesian (x,y,z), projected from the centre of the sphere to the earth surface, returns cartesian (x,y,z) used to calculate "true" centre of set of lat longs

Usage

```
pro2sph(x, y, z)
```

Arguments

x	East to West coordinate in metres
y	South to North coordinate in metres
z	height coordinate in metres

Value

x,y,z

Note

http://stackoverflow.com/questions/9604132/how-to-project-a-point-on-to-a-sphere

Author(s)

Justin Moat. J.Moat@kew.org

References

Descartes, R., 1637. Discours de la methode. A Leyde, De l'imprimerie de I. Maire, Paris.

rad2deg *Radians to Degrees*

Description

Calculates radians from degrees or degrees from radians

Usage

```
rad2deg(rad)
```

Arguments

rad	number in radians

Value

number

Author(s)

Justin Moat. J.Moat@kew.org

Examples

```
b <- 0.392699
rad2deg(b)
```

simProjWiz *Simple Projection Wizard*

Description

Projects any set of lat long points to a "suitable" area projection, based on it's "true centre of gravity"

Usage

```
simProjWiz(thepoints, thecentre)
```

Arguments

thepoints	set of points in latitude and longtitude ie c(lat,long)
thecentre	one point ie c(lat,long)

Details

Simple equal area projection wizard

Value

set of points in metres (x,y)

Note

Based around a simple continental projection, using two sets of projections equal area cylindrical = Cylindrical equal-area = 8287 equal area azimuthal for polar (above 70) = Lambert azimuthal equal-area

note these are not cartographically pleasing projections, they are just so we can get the data into something simple for areal analysis See below for a more cartographically pleasing projection engine

Šavric, B., Jenny, B., Jenny, H., 2016. Projection Wizard – An Online Map Projection Selection Tool. Cartogr. J. 53, 1–9. doi:10.1080/00087041.2015.1131938

Author(s)

Justin Moat. J.Moat@kew.org

References

Šavric, B., Jenny, B., Jenny, H., 2016. Projection Wizard – An Online Map Projection Selection Tool. Cartogr. J. 53, 1–9. doi:10.1080/00087041.2015.1131938

Snyder, J.P., 1987. Map projections: A working manual, Professional Paper. Washington, D.C.

Examples

```
lat <- runif (200,-24,-12)
long <- runif (200,43,51)
ll <- data.frame(lat,long)
cp <- trueCOGll(ll)
pointsprojected <- simProjWiz(ll,cp)
```

---

trueCOGll *True centre of gravity from a set of Lat longs*

Description

Calculates the "true" centre of gravity (weighted) from a set of lat longs, using cartesian geometry

Usage

```
trueCOGll(thepoints)
```

Arguments

thepoints	set of points c(lat,long)

Value

a point (lat,long) from centre

Author(s)

Justin Moat. J.Moat@kew.org

References

Descartes, R., 1637. Discours de la methode. A Leyde, De l'imprimerie de I. Maire, Paris.

Examples

```
lat <- runif (200,-24,-12)
long <- runif (200,43,51)
ll <- data.frame(lat,long)
cp <- trueCOGll(ll)
```

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rCAT: Species Conservation Assessment tools in R:

Introduction and tutorials

Author: Justin Moat[1,2]

Contributors: Steve Bachman[1,2]

January 12, 2017

Document version: 1.1

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1 Introduction

Red Lists are widely used to indicate species at risk of extinction. The tools presented here are scripts that integrate with primary occurrence data, to produce preliminary conservation assessments and to help assessors generate full species conservation assessments.

These tools are to be used with specimen data or sighting data with latitude and longitude co-ordinates and have been primarily designed to work with herbaria data which provides an important source of data relevant for Red List assessments.

The tools follow the IUCN Red Listing guidelines (IUCN 2012, 2016), and produce data for Extent of Occurrence (EOO) and Area of Occupancy (AOO).

The conservation ratings given here, although calculated based on IUCN categories and criteria, are not equivalent to full IUCN ratings submissible for publication on the IUCN Red List. The majority of measures presented here relate to geometry and species range measures which focus on just one aspect of threat considered in the IUCN categories and criteria. Use of these tools assumes the user is familiar with the Red List Criteria (IUCN 2012, IUCN 2016).

However, the measures calculated do provide a good initial estimate of threat and can be used as a baseline for more detailed assessments that can incorporate population data, further literature, additional GIS analysis and consultation with experts and specialists.

These tools are primarily produced for quick assessment with the emphasis on speed of processing. Presently these tools do not produce any graphic or visual outputs. Use R's graphic outputs or http://geocat.kew.org/ to visualise the data and investigate your species in the context of other mapping layers.

1.1 Brief history

These tools are formed and built on previous tools. A brief history of development is presented below for context and reference:

- 2003, first tool produced for ArcView 3.0 as used in Willis *et al*. 2003
- 2007, public release of cats.avx = Extension for ESRI ArcView 3.1 (Moat. 2007)
- 2011, release of GeoCAT online tools geocat.kew.org (Bachman *et al* 2011)
- 2017, release of rCAT

1.2 Script development

Further improvements to the tool will be included in future releases. Note that any strikethrough text refers to functions that will be introduced at a later date.

1.3 Discussion

1.3.1 Cases of vagrancy, georeferencing and error checking

Care must be taken when using species spatial data in any analysis. Erroneous or incorrect outlying points or cases of vagrancy should be excluded and georeferencing should be error checked prior to analysis. There are no data cleaning tools within rCAT, but many other tools

and methods now exist to aid georeferencing and to describe errors for georeference uncertainty.

Specifically, in R see:

> biogeo https://cran.r-project.org/web/packages/biogeo/index.html (Robertson 2016) and related paper: http://onlinelibrary.wiley.com/doi/10.1111/ecog.02118/full

Also see:

- See Wieczorek et al (2004) and the following links for details:
- http://bg.berkeley.edu/latest/
- http://manisnet.org/GeorefGuide.html
- https://github.com/VertNet/api-geospatial/blob/master/GeospatialQuality.md

  Related paper: http://bioinformatics.oxfordjournals.org/content/early/2016/02/16/bioinformatics.btw057.short

- http://www.gbif.org/prog/digit/Georeferencing
- http://www.museum.tulane.edu/geolocate/default.aspx
- http://www.diva-gis.org/

1.3.2 Extent of occurrence (EOO)

The IUCN Guidelines (Version 12 – February 2016) provides useful discussion of the problems associated with estimating EOO. The minimum convex polygon (MCP), as used here, has previously been criticised due to the coarse level of resolution on its outer surface (Ostro et al. 1999). However, the MCP is still considered a useful approximation of EOO as the purpose of EOO is to measure the degree to which risks from threatening factors are spread spatially across the taxon's geographical range (Joppa *et al*. 2015). When EOO is applied to criteria other than B1, such as reductions (criterion A) or continuing declines (B and C), then the MCP may no longer be the most appropriate measure as it is sensitive to outliers and sampling effort. An alpha hull may be more appropriate in this situation (Burgman and Fox, 2003).

1.3.3 Area of occupancy (AOO)

The problems associated with scale and AOO measurements are well described in the IUCN guidelines. The tools in this extension allow the user to define a grid cell length in metres. ~~In addition a sliding scale grid cell width is suggested which is scaled to the EOO measurement (Willis et al 2003).~~ The IUCN recommended scale of a 2 x 2 km grid (4 km^2) can be applied but may not be appropriate if the point distribution does not fully represent occupied areas. In this case the assumption will be that areas without points are confirmed absences whereas this may simply be an artefact of collection effort. The approach described above is deemed suitable for a preliminary assessment, but for a full assessment it is advised that the AOO measure is more carefully defined e.g. by using a downscaling approach (Marsh 2016) or using habitat maps derived from remote sensing imagery or range prediction models. The IUCN guidelines document should be consulted when using habitat maps as estimates for AOO.

1.3.4 Vulnerable D2 (VU D2)

As well as the B criterion the AOO measure can also be applied to the D criterion under Vulnerable (VU) D2. If AOO is restricted such that the population is prone to the effects of human activities or stochastic events and may become Critically Endangered or Extinct in a short time period then VU D2 may be appropriate. However, although a guideline threshold

of 20 km^2 is suggested by IUCN this is not intended to be exclusive and therefore it is not reported in the preliminary IUCN results created by this tool.

1.3.5 AOO and EOO thresholds

We have used the thresholds described in the IUCN Red Listing guidelines (IUCN 2012, 2016). We have also adopted the Near Threatened threshold following the examples given in IUCN Standards and Petitions Subcommittee guidelines version 11 (2014). Summary of these thresholds and abbreviations are in the table below.

IUCN Rating	Rating abbreviation	AOO threshold (km^2)	EOO Threshold (km^2)
CRITICALLY ENDANGERED	CR	< 10	< 100
ENDANGERED	EN	< 500	< 5,000
VULNERABLE	VU	< 2,000	< 20,000
NEAR THREATENED	NT	< 3,000	< 30,000

Table 1. IUCN category thresholds used rCAT

2 General rCAT usage

This is a relatively simple package, with several additional routines for data manipulation. The general work order is:

1. Import of species occurrence data in geographic projection e.g. latitudes and longitudes. If data is already projected to meters, skip point 2 below*
2. Project geographic data to suitable area projection in metres. N.B. this can be either for all species, if for a localised area or individual species for more widespread species data. We use the geographic centre of the set of points to project the data.
3. Calculate EOO area and AOO area
4. Return IUCN categories for EOO and AOO areas

* The assumption is that the data is cleaned, is in decimal degrees and represents wild occurrences of the taxon to be assessed. See 1.3.1 for discussion and list of tools to support data cleaning.

3 Tutorial

3.1 Installing rCAT package

To install the package from CRAN

```
install.packages("rCAT")
```

To load the library

```
library ("rCAT")
```

3.2 Quick single species example

As a quick example, we'll import and produce metrics for a single species. The data we'll use is dummy data, in csv from geocat.kew.org. I have added this dummy data into this package

to retrieve this data use system.file("extdata","species_x.csv",package="rCAT". To use you own data replace this with your file (ie my_data.csv)

```
mydata <- read.csv(system.file("extdata","species_x.csv",package="rCAT"))
```

The lat (*mydata$latitude*) and long (*mydata$longitude*) fields are needed for any analysis.

```
mypointsll <- data.frame(lat=mydata$latitude,long=mydata$longitude)
```

To project the data automatically to an area projection we are going to use the projection wizard, firstly we'll need to get the true geographic centre of the points.

```
#find the true centre of the points

centreofpoints <- trueCOGll(mypointsll)

#project to an equal area projection

mypointsxy <- simProjWiz(mypointsll,centreofpoints)
```

We now have a set of points (mypointsxy) in an equal area projection in metres, ready to calculate EOO in km^2. Note area is calculated in m^2, so we need to convert to km^2. Also area is returned as negative (as polygon is constructed anticlockwise)

```
#Calculate the Extent of Occurrence EOO

EOOm2 <- EOOarea(mypointsxy)

EOOkm2 <- EOOm2/1000000
```

Now for the AOO in km^2. Note AOOsimp returns the number of cells not the area and cellsize is the length of one side of the square cell in metres

```
#Calculate the Area of Occupancy AOO for 2km cells

cellsizem <- 2000

AOOnocells <- AOOsimp (mypointsxy,cellsizem)

AOOkm2 <- AOOnocells * (cellsizem/1000)^2
```

To return the IUCN category for these EOO and AOO values. Note the second parameter triggers return of the full text or the abbreviation for the IUCN category.

```
#review the IUCN category for this AOO and EOO Area

EOOcat <- EOORating(EOOkm2,FALSE)

AOOcat <- AOORating(AOOkm2,FALSE)
```

Results are in km^2 are below with the IUCN categories:

```
#show results

> EOOkm2

[1] 585915.6

> EOOcat

[1] "Least Concern"

> AOOkm2

[1] 56

> AOOcat

[1] "Endangered"
```

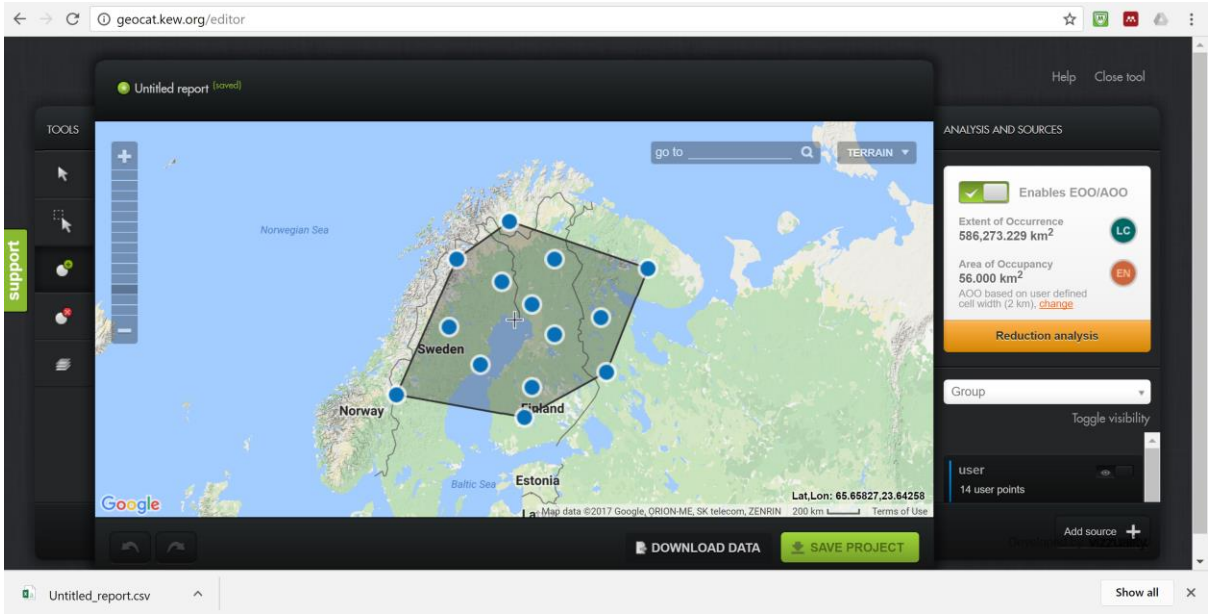


Figure 1. Results for species x in GeoCAT

3.3 Batch processing

The above example is for a single species, but the code is designed to perform with large numbers of species and across large databases. Here we will work with a dummy dataset of 4 species (w,x,y and z).

- Species w is a global (land and sea) species
- Species x as above single species example
- Species y is a Peru only species
- Species z is a North polar species

First step is to read the dataset and also get a unique list of species. I have suppled a dummy dataset for testing system.file("extdata","multiple_species.csv",package="rCAT"), but you can replace this with your dataset i.e. myfile.csv

This csv is formatted:

```
scientificname,latitude,longitude
```

```
species x,67.06743335,22.5

species x,65.36683689,17.578125

species x,62.59334083,12.65625

species x,62.91523304,25.3125
```

We will use the function ConBatch with combines all the routines into one simple function, returning a dataframe (table) or results by species

First step is to read the dataset. I have suppled a dummy dataset for testing `system.file("extdata","multiple_species.csv",package="rCAT"),` but you can replace this with your dataset i.e. `myfile.csv`

```
#read in simple csv data

mydata <- read.csv(system.file("extdata","multiple_species.csv",package="rCAT"))
```

Next is to call ConBatch, in this case we are using a cell length of 2000m (2km). The final argument is either TRUE or FALSE. True is where all data is projected together using the centre of all latitudes and longitudes. FALSE each species is projected separately. I would suggest you use TRUE if data is all from a similar area (i.e. all from one country/region), as this will speed up processing.

```
results <- ConBatch(mydata$scientificname,mydata$latitude,mydata$longitude,2000,FALSE)
```

Final results are in dataframe results. If you wish to save this as a csv:

```
write.csv(results, file="results.csv)
```

	taxa	NOP	MER	EOOkm2	AOO2km	EOOcat	AOOcat
1	species x	14	918562.259811711	585915.607417865	14	LC	EN
2	species y	124	1717224.64389286	634149.482670821	124	LC	EN
3	species z	61	22622717.2314339	17839113.1220552	61	LC	EN
4	species w	1130	509390660.388499	506445176.073246	1130	LC	VU

Table 2. Example results from ConBatch for dummy dataset

3.4 Multiple species example (step through)

The above example is very simple, but not flexible. The functions in rCAT are atomises so you can call each individually. The example below, uses the same data as above, stepping through each conservation metric, but testing two cellsizes.

As above first step is to read the dataset and also get a unique list of species. I have suppled a dummy dataset for testing `system.file("extdata","multiple_species.csv",package="rCAT"),` but you can replace this with your dataset i.e. `myfile.csv`

```
#read in simple csv data

mydata <- read.csv(system.file("extdata","multiple_species.csv",package="rCAT"))

mypointsll <-
data.frame(taxa=mydata$scientificname,lat=mydata$latitude,long=mydata$longitude)

specieslist <- unique(mypointsll$taxa)
```

Next to build a data frame to store the results

```
#make a dataframe to store resultsresultsdf<- data.frame(taxa=character(),NOP=integer(),
MER=double(),EOOkm2=double(),AOO2km=double(),AOO100km=double(),stringsAsFactors=F
ALSE)
```

We then just need to loop through each taxon, extracting one at a time.

```
for (taxa in specieslist){

print(paste("Processing",taxa))

taxapointsll <- (mypointsll[mypointsll$taxa==taxa,c("lat","long")])

}
```

As for single species we'll re-project to an equal area projection and then calculate the various metrics we need. In the example script we calculate:

Column heading	Description
Taxa	Species name
NOP	Number of points used for analysis
MER	Area of the minimum enclosing rectangle in km^2
EOOkm2	Area of EOO in km^2
AOO2km	Number of cells for a 2 x 2 km cell (4 km^2)
AOO100km	Number of cells for a 100 x 100 km cell (10000 km^2)

Table 3. Column headings for results dataframe

Implementing the loop above, with all of the analysis (note loop repeated from above for consistency).

```
for (taxa in specieslist){

print(paste("Processing",taxa))

#extract one taxa

taxapointsll <- (mypointsll[mypointsll$taxa==taxa,c("lat","long")])

#reproject points

 taxapointsxy <- simProjWiz(taxapointsll,trueCOGll(taxapointsll))


 #CALCULATE METRICS

 #number of points

 nop <- nrow(taxapointsxy)

 #Minimium enclosing rectangle
```

```
MERps <- MER(taxapointsxy)/1000

MERarea <- (MERps[2] - MERps[1]) * (MERps[4]- MERps[3])

#EOO

EOOa <- EOOarea(taxapointsxy)/-1000000

#AOO with 2 x 2 km cells

AOO2km <- AOOsimp(taxapointsxy,2000)

#AOO with 100 x 100 km cell

AOO10km <- AOOsimp(taxapointsxy,100000)

#finally in this loop we need to populate the dataframe

#with the results for each taxon

resultsdf[nrow(resultsdf)+1,] <- c(taxa,nop,MERarea,EOOa,AOO2km,AOO10km)

} #end of loop
```

Final results are in the dataframe resultsdf:

	taxa	NOP	MER	EOOkm2	AOO2km	A00100km
1	species x	14	918562.259811711	585915.607417865	14	14
2	species y	124	1717224.64389286	634149.482670821	124	65
3	species z	61	22622717.2314339	17839113.1220552	61	61
4	species w	1130	509390660.388499	506445176.073246	1130	1111

Table 4. Example results for dummy datasets

If you wish to save the results as csv*:*

```
write.csv(resultsdf,file="results.csv)
```

4 Bibliography (essential reading)

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Appendix II: List of other publications during the study period

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Baena S., Boyd D.S. and **Moat J.** (2017). UAVs in pursuit of plant conservation – Real world experiences. *Ecological Informatics.* https://doi.org/10.1016/j.ecoinf.2017.11.001

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Parnell J.A.N, Pilla F & Thai Biogeography group…**Moat J.** … (2015) … A re-examination of the life and work of A.F.G. Kerr and of his colleagues and friends. *Thai Forest Bulletin* 43, pp 111-131. http://www.dnp.go.th/botany/PDF/TFB/TFB43/TFB43_18_p111-131.pdf

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Gibraltar 11th to 16th July 2015 (pp. 108–111). Gibraltar: UK Overseas Territories Conservation Forum. www.ukotcf.org.

Appendix III: code

See GitHub for r code https://github.com/gistin

See CRAN for rCAT code https://cran.r-project.org/package=rCAT

Appendix IV: Research timeline

The work, analysis and findings in this thesis have had a long inception. Deriving in the main from two strands of my research: 1. Spatial metrics for species conservation (Willis, Moat and Paton, 2003; Bachman *et al.*, 2011) and 2. Climate change modelling for plant species (Davis *et al.*, 2012).

The spatial metrics for conservation are driven by a need from within the conservation community, for simple, robust and reproducible metrics to determine a species risk of extinction from specimen data (Bachman *et al.*, 2011). This was initiated in an ArcView toolbox (Willis, Moat and Paton, 2003; Moat, 2007), which would visualise specimen data and calculate species spatial metrics (AOO, EOO, fragmentation etc.). With the advance in online computing and data providers (like GBIF) opening up APIs, this allowed these algorithms to advance into a user friendly browser based interface: GeoCAT (Bachman *et al.*, 2011; Moat, Vizzuality and Bachman, 2017), which is frequently used and cited. I have continued to develop these algorithms, and to increase flexibility released an R (R Core Team, 2016) version (Paper VI) and made improvements to the AOO algorithms (Paper V).

Climate modelling using SDMs has advanced with open access to global gridded climate datasets (i.e. BIOCLIM (Busby, 1991), downscaled future climate datasets (i.e. from CGIAR (CGIAR/CCAFS, no date), in conjunction with the advancement of the models and algorithms (i.e. Maxent (Phillips and Dudik, 2008) and BIOMOD (Thuiller *et al.*, 2009; Thuiller, Georges and Engler, 2014). The question of Arabica coffee started with a simple observation in Ethiopia, that coffee farmers were having difficulties with Arabica coffee production, against a backdrop of ever increasing temperatures and declining rainfall. This started the ball rolling: I used data from herbarium collection data (including RBG, Kew) collated over many years, and existing wild specimen coffee data, to see if there was a climate signal and

if this would be affected by changes in climate. This culminated in the first paper (Paper I[a]) underpinning this thesis. This paper produced a huge amount of publicity and interest, which prompted the Department for International Development (DFiD) to approach us to build on these early findings, in order to help build a climate resilient coffee economy for Ethiopia. We built up a three year and £400k project, which was funded by the Strategic Climate Institutions Programme (SCIP) in Ethiopia. Within the project 'Building a climate resilient coffee economy for Ethiopia' I developed the climate modelling side to be as robust and as rigorous as practically possible, covering both wild and cultivated Arabica coffee. The outputs from this project were for multiple stakeholders and audiences and resulted in Papers II, III and IV[a].

The final two papers (VII and VIII), bring together these two strands of research (along with additional background research), applying the newly developed spatial conservation tools to the SDMs and climate change models for Arabica coffee, concluding in a conservation status of 'Endangered' for the species, under a changing climate.

Appendix V: Additional ground truthing and field observations

"Lies, damned lies, and statistics"

[Attributable to various historic figures, including Disreali: "there are three kinds of lies: lies, damned lies and statistics"]

Readers, reviewers and users often do not trust or understand modelling, statistics and their inherent uncertainties. Within Papers I[a] and II I deal with sampling bias, the choice of GCM, the choice of climate variables for the modelling (and therefore covariance) and finally with the choice of SDM model method (finally using the SDM ensemble method (Thuiller, Georges and Engler, 2014)). This is very difficult to convey to the public, who often find the discussion, conclusions and results too abstract.

To tackle this issue initially, a huge amount of ground data was gathered to test the models and assumptions, and to collect empirical evidence. Whilst collecting ground-truthing data a simple assessment of coffee plant stress was made. At each of the ground points (georeferenced, from 2013–2016) we recorded stress into five rankings (from Paper II):

1. **None:** plants appear healthy with turgid leaves.
2. **Mild:** leaves with slight to moderate wilting.
3. **Medium:** leaves with obvious wilting (held at least 45° from the horizontal plane) and with slight folding (upwards) along the main (midrib) axis.
4. **Severe:** leaves wilting, with distinct folding along the main axis, and either falling or easily detached from the plant.
5. **Death:** plants dead: all leaves fallen, wood brittle and dry.

In several sites, climate data-logging equipment was installed by the ground survey team. The data collated from these loggers did not cover a long enough period (two to three years) for detailed analysis but did provided a good indication of the response of Arabica coffee to climatic variables through each coffee-growing season (one year), and niche model suitability, in the real world.

Also, during the field work we informally interviewed farmers for perceived changes in coffee farming, on a yearly and a generation-by-generation basis.

From both the interviews with farmers and the evidence from ground-truthing we observed that areas categorised by us as Unsuitable or Marginal would have poor and inconsistent harvests, produce lower quality coffee and in extreme circumstances (for example, drought episodes) coffee trees would experience severe stress or death. Three major examples of non-empirical evidence that corroborate our models and show agreement with the near (2010-2039) SDM future predictions:

1. In the Zege Peninsula, near Bahir Dar (on the shores of Lake Tana), coffee farming is challenging. The farmers report a long-term reduction in productivity, from good harvests every year or two in the mid-1930s, to harvests every five from the 1990s onwards. Our models show the suitability of the area as Marginal (1960–1990) to Fair (2010–2039), and then Unsuitable (2040–2099), with very strong model agreement. The major climate constraint for Zege is not total annual precipitation, but the prolonged dry season.
2. In the central and eastern parts of the Wellega coffee area, the SDM niche suitability (1960–1990) is categorised as Marginal. Farmers and producers reported increasingly erratic harvests (every three years or more), which is attributed to a shift to less precipitation that started in the late 1970s.
3. For the Harar coffee Zone, the niche is categorised as Unsuitable by 2010–2039, which is a good indication of conditions observed on the ground in the region. Coffee farming is very difficult (sub-optimal) unless some interventions are in place (i.e. irrigation and terracing) or where environmental conditions can assist (i.e. where the local water table brings sufficient water to the plants). We also received numerous reports from farmers and coffee sector workers of a long-term decrease in precipitation in the Harar coffee zone and a steady, long-term decline in coffee farming over several decades (since at least the 1960s and probably before).

Finally, whilst doing this work, we worked closely with the BBC (http://www.bbc.co.uk/news/resources/idt-fa38cb91-bdc0-4229-8cae-1d5c3b447337) to bring our findings to life and to a wider audience (see Discussion and Impact chapters, after the main papers), which included independent video interviews with coffee farmers and producers, which corroborated our findings.

Appendix VI: Scales used for visualisation

When using a printed mapping scale, it is necessary to represent (trying not to mis-represent) the data used, while balancing the user's needs and expectations. The data (see table below) used in this thesis are at multiple scale and resolutions. I use resolution/precision, loosely, as the measure of precision or detail of a feature or pixel (a combination of grain size and extent (Turner *et al.*, 1989)).

	Resolution/precision (m)	**Notes**
Specimens and observations	3 to 1000	Species and observations with locational error over 1km were removed. Data were collected with locational error recorded following (Wieczorek, Guo and Hijmans, 2004)
Climatic data	1000	Resolution of gridded data was at 1 km, but these data are modelled from weather station data at multiple resolutions and accuracy (Busby, 1991; Hijmans *et al.*, 2005)
Satellite imagery	30	Landsat imagery (United States Geological Survey, 2015)
Protected areas	~ 1000-10,000	Multiple scale and accuracy used here (IUCN & UNEP-WCMC, 2016)
Elevation data	90	STRM hole-filled (Jarvis, A. *et al.*, 2008)
Cartographic data (rivers, roads, features)	3 to 25,000	Data used as background and illustrative for mapping and cartographic outputs, from field work (@ 3m resolution GPS) to general mapping for Ethiopia (Water and Land Resource Centre Addis Ababa Univeristy, 2016)

Table 8. Primary datasets with resolution used in coffee manuscripts (Papers: I[a], II, III, IV[a] VII & VIII)

The outputs from all the analyses were presented at different scales, depending on the media and audience. For example, in the main coffee papers (I[a], II and VII) the print scale was approximately 1:6,500,000 to 1:20,000,000 (i.e. 1 mm on the page equals 6.5 to 20 km); here the fine-resolution details are lost, but the trends and overall feel can be visualised in a few graphics. In the *Coffee Atlas of Ethiopia*, where detail is needed on the ground by coffee buyers, producers, sector workers and exporters, I used a scale of 1:700,000; at this scale, much of the detail of the mapping can be represented. The true scale of our mapping for the forests from Landsat imagery could have been pushed to approximately 1:125,000 (United States Geological Survey, 2015), but as all other datasets had much lower resolutions and we

needed to keep the number of pages manageable, I compromised with a scale of 1:700,000, which resulted in 41 pages at A4 size (Paper IV[a]).

Appendix VII: Details of impacts for Manuscripts I[a], II and III

Paper I[a]

This paper provided the background that showed there was a likely response of coffee in Ethiopia under a changing climate. The publicity that it gained was impressive, with the BBC outputting quality broadcasts and web pages (Figure 25). This publicity came to the attention of DFiD and specifically the SCIP initiative in Ethiopia, from which they invited Kew to apply for funding for a much larger and more in-depth project to ultimately build a climate-resilient coffee economy for Ethiopia. To date this paper has received 121 citations and over 72,000 views and downloads; it also made it into the *PLoS ONE* 'Ecological Special'. It as an Altmetric score of 992 (In the top 5% of all research outputs scored by Altmetric https://www.altmetric.com/details/1054783?src=bookmarklet).

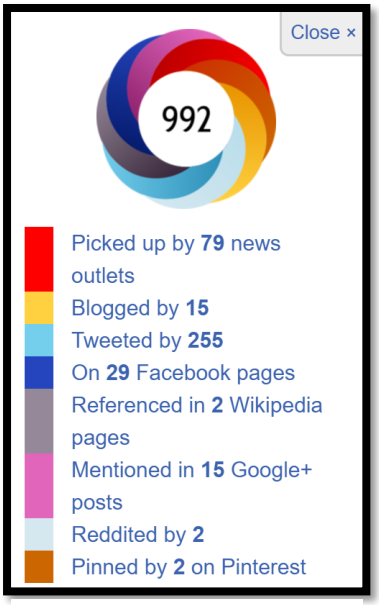


Figure 25 Altmetrics scores for Paper I[a]

Papers II & III

After just six months Paper II it has an Altmetric score of 629 (Putting it in the top 5% of all research outputs scored by Altmetric https://www.altmetric.com/details/21174779, figure 26.).



Figure 26 Altmetrics scores for Paper II

In line with Paper I[a], these two papers produced a huge amount of publicity (see below), but also put coffee under climate change into a new light, and diverse and global audience is now discussing the findings (or at least tweeting them). We worked closely with the BBC to produce a 'story centrepiece' webpage (http://www.bbc.co.uk/news/resources/idt-fa38cb91-bdc0-4229-8cae-1d5c3b447337) (Figure 27). This increased the reach of the story as it was released in 16 different languages. The

science reached all habitable continents. Up to 13/07/2017 (approximately one month after release), the BBC web pages had over 350,000 views, with each visitor engaging on average for 1 minute and 40 seconds (which is a long time). It even made it to BBC TV (BBC News), Al Jazeera, and multiple radio platforms, three mainstream UK radio stations, (including BBC's Inside Science), multiple USA and at least five Canadian radio interviews, and numerous printed press outputs (including the Guardian, Daily Mail and Glamour Magazine!), and numerous new blogs and papers (over 75 at the last count). The findings of our study had immediate take up in Ethiopia, where two events are planned (2017-2018), one with Government stakeholders and the Ethiopian Academy of Sciences, which will be in October, and another with the Tea Development and Marketing Authority, in November. Both publications have been very well received by both peers and politicians:

"Ethiopia is doing its level best to combat climate change through the development of renewable energy and the introduction of modern farming technologies, including soil and water conservation. There is no doubt that this study will contribute hugely to developing a climate resilient coffee economy in Ethiopia and other countries. The Ethiopian coffee sector could definitely benefit from these endeavours, so that coffee growers can retain their fair share of the global market." **H.E. Dr. Hailemichael Aberra Afework, Ethiopian Ambassador to the UK.**

The new research is a "brilliant piece of work". "This is the only comprehensive, country-specific study I have seen that uses some of the best methods in climate modelling coupled to very rigorous ground-truthing – extremely useful for governments and industry and a model to be repeated.". **Dr Tim Schilling, Chief Executive of World Coffee Research.**

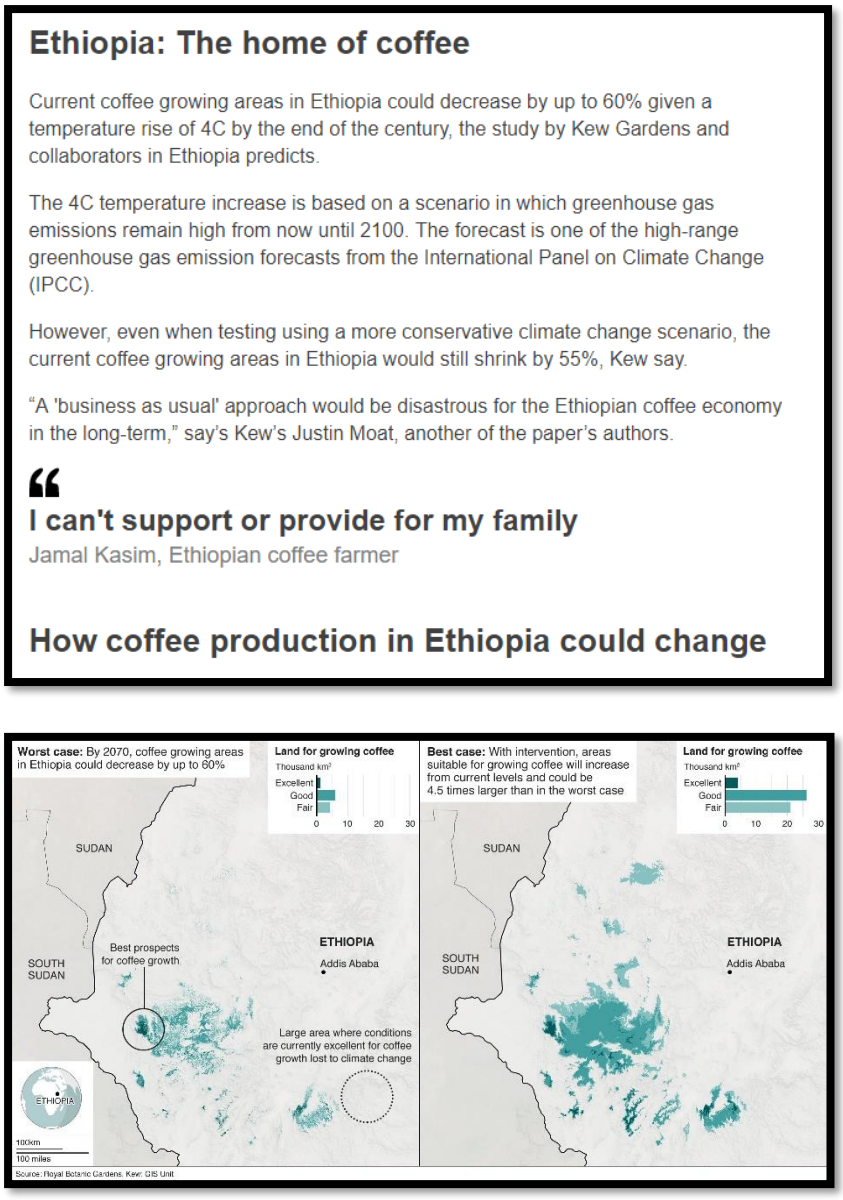


Figure 27 Screen captures of part of the BBC web story "Coffee under threat"

Appendix VIII: Economic impacts

One original ambition, through all the coffee work, was to help build a climate-resilient coffee economy for Ethiopia. During the project, the project was independently assessed as a case study for its economic impacts. This was published in 2016 in the *Kew Valuation Report* by Oxford Economics (Oxford Economics, 2016).

> *"COFFEE IN ETHIOPIA*
> *Ethiopia is the world's third largest producer/exporter of Arabica coffee. It provides more than 30 percent of the country's export earnings, totaling around US$ 350 million. It is estimated that 25 percent of Ethiopia's population (some 20 million people) depend directly or indirectly on coffee for their livelihood; and in south west Ethiopia coffee is the main provider of household income.*
>
> *Building a climate resilient coffee economy for Ethiopia*
> *…*
> *Before RBG Kew conducted the study, there were few resources for understanding and managing the risks associated with climate change and land-use change in Ethiopia. The study has provided the information needed to sustain the Ethiopian coffee industry in the context of a changing climate and land use, helping to support the livelihoods of the 20 million or so Ethiopians who rely on coffee production."*

The above report lacked detail, in that it did not give a monetary value for the impact of the project, and was also incorrect about the export earnings (which should have been in the region of $500 to $800 million (Minten *et al.*, 2014)). Reviewing this afresh, as outlined below, the impact is much greater.

Today, an estimated 525,000 hectares (5,250 km^2) of coffee are planted in Ethiopia (Tefera and Tefera, 2014), although the actual dedication of land for coffee (cultivated, semi-cultivated and wild) is close to 23,000 km^2 (Paper II). It is hardly surprising that coffee provides Ethiopia with its most important agricultural commodity, contributing around one quarter of its total export earnings (Minten *et al.*, 2014). In 2014/15 Ethiopia exported around 180,000 metric tonnes of coffee (International Coffee Organization (ICO), 2016) at a value in excess of $800 million USD. Ethiopia is Africa's largest coffee producer and the world's fifth exporter of Arabica coffee, after Brazil and Colombia (International Coffee Organization (ICO), 2016), even though yields (per unit area) are low compared to other producing countries. Coffee farming alone provides a livelihood income for around 15 million Ethiopians (16% of the population), based on four million small-holder farms (Minten

et al., 2014; Tefera and Tefera, 2014). For many of these farmers, coffee is their single most important source of income.

If we look at the potential for increased productivity, by going from the area presently occupied in 2016 to the potential that coffee could occupy by 2036, this is more than four-fold. Restricting to only a two-fold increase, which represents an achievable figure, the potential increase in revenue up to 2036 would be a staggering $31 billion USD (or $1.5 billion per year), based on an $800 million USD export value in 2014/15 and composite coffee prices remaining the same (they were not high and could easily double). Potentially it could be almost $3 Billion for the last year. We should not forget that this does not include the domestic (non-export) market, which accounts for around half of all coffee production in Ethiopia (export prices closely match domestic prices).

If only 10% of this intervention is realised it would amount to an increase in revenue of $3 billion USD over the next 20 years ($150 million USD per year). Of course, investment costs are not factored in, which would include afforestation, reforestation, forest preservation, compensation, and the establishment of new farms, etc. These have costs, of course, but also their own benefit. In addition, I would project that at least $200,000 a year could be saved in better targeted interventions by NGOs, although our feeling, based on discussions so far with NGOs (before the release of paper II and IV[a]), is that this could be significantly more.

There is also the marketing potential of the *Coffee Atlas of Ethiopia*, which could have an impact as early as the 2018/19 harvest. One private firm is doing similar work this in the Brazilian coffee sector, although their methods and reach are slight in terms of complexity and coverage compared to the SCIP project; it charges $10,000 for a single-use copy of its report.

In summary, it is hard to give exact figures, but it would seem that at least $300 million could be saved/earned as a result of our findings, if the interventions we suggest based on our scientific findings are followed. Given the cost of the SCIP project ($350K) this would be an excellent return-on-investment (approximately 1000 times return on investment).

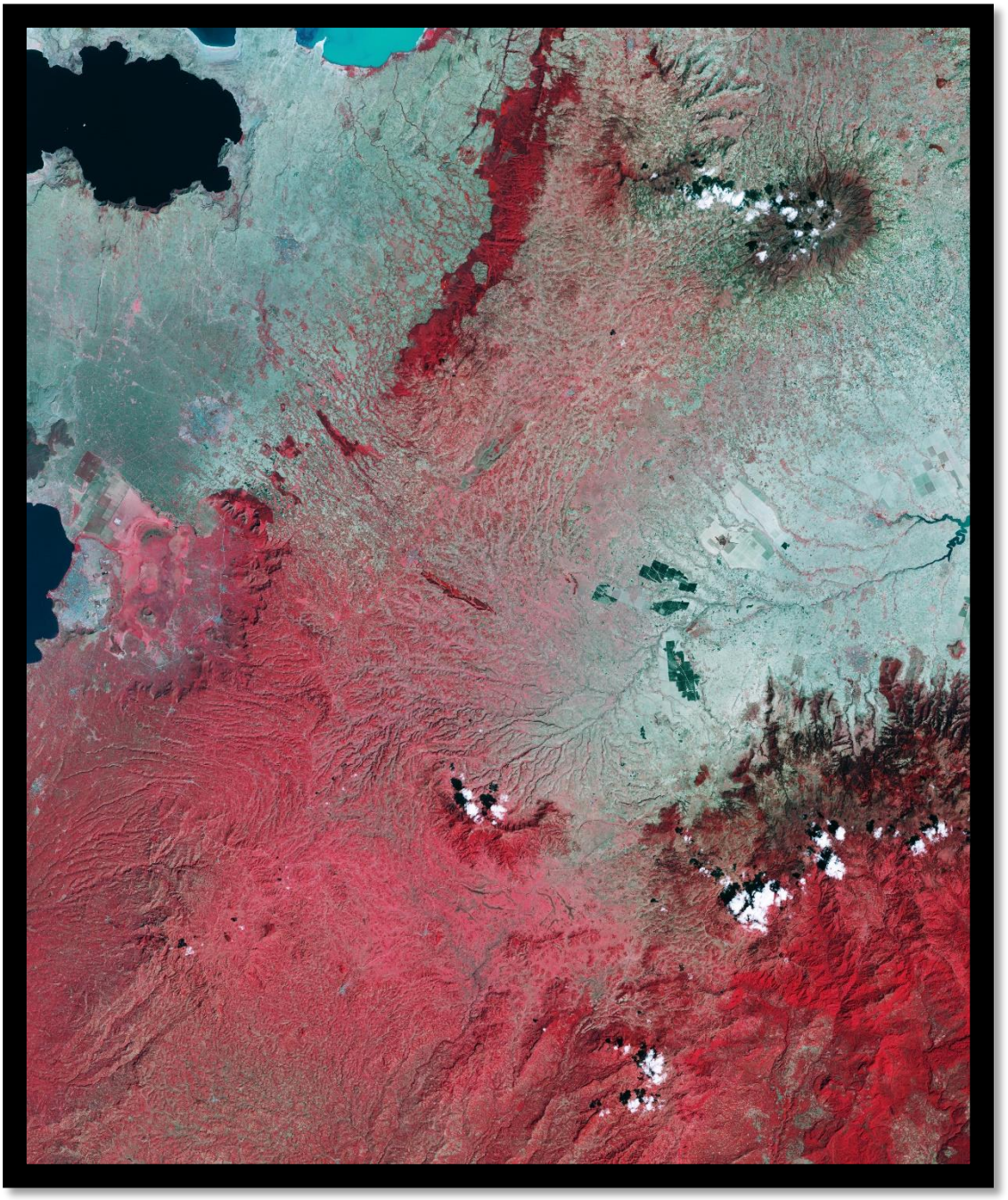


Figure 28 Landsat False Colour composite of coffee forest in Sidamo

Landsat 8 image from 2014 of the Sidamo coffee area in SE Ethiopia. In this area, coffee forest is already being affected by changes in climate. Darker red represents denser vegetation (Image: Justin Moat).