Front Matter

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Executive Summary

This report provides new evidence on the present and predicted future impacts of climate change on coffee production and markets.

Coffee is sensitive to climate. Arabica coffee is grown at high elevations, in warm regions, with sensitive quality, and multiple positive and negative ecosystem interactions (**??**). All of these can cause high-quality coffee to be threatened by climate change.

Temperatures are already causing shifts. Recent temperatures in the coffee belt have been increasing by 0.16°C per decade (1.1), representing an average poleward shift of 46km per decade. In Brazil, low elevation farms are already being impacted (**??**).

Temperature across the coffee belt is expected to rise by 2.1°C (likely range 1.7 - 2.5°C) by 2050 (1.2). Average future temperatures have high predictability, but uncertain spatial patterns. 60-64% of recent temperatures is explained by a trend, but most of the rest is uncertain year-to-year (1.1.2).

Precipitation across the coffee belt is expected to increase 1.7% (likely range -0.1 - 3.2%), but dry periods will often be drier (1.2). Average future precipitation has low predictability. Only 1% of precipitation can be explained by long-term trends, but decadal cycles predictable in the short-term (like El Niño) play a large role.

We develop a new database of spatial coffee production. The database combines spatial data from 3 global sources and 8 detailed country sources, and temporal data from 2 global sources and 5 country sources (**??**).

We present a new technique for coffee suitability analysis. The technique incorporates properties of soil, climate, and elevation for a statistical model, and combines it with biological conditions from the Global Agro-ecological Zones (GAEZ) project (3.3).

On average, El Niño years produce 30% hikes in coffee prices and drops in coffee yields. No corresponding effect is seen globally across La Niña years, except in their interactions with the PDO and AMO signals (**??**).

Higher temperatures may lead to larger coffee rust outbreaks. In addition, vigilant farmer action against these outbreaks will decrease small infestations but may increase the probability of large ones (**??**).

Hot days produce large yield losses. In Brazil, even an hour over 35°C cause serious losses, and some countries receive losses at temperatures as low as 33°C (**??**). There is evidence that some countries have adapted to high temperatures with lower sensitivity to them.

Under temperatures in 2050, average yields in existing growing areas are expected to drop 20%. The variation between countries is large, with some countries losing the majority of their production potential, and others seeing increases (**??**).

Globally, prices paid to farmers are driven much more by international prices than local competition. We also find that international prices and consumer demand are more self-determined than driven by changes in production and retail prices, respectively (6).

Most of the markup associated with producer countries does not go to farmers. Trade relations suggest that 21% of consumer prices go to production, 44% to distribution, and 35% to the organizations in the consumer's country (**??**).

Nearly 20 countries could lose all naturally highly suitable coffee land. Globally, suitable regions will decrease by 56% for Arabica, including 24% of current cultivation, while they increase by 87% for Robusta. (3.7).

New coffee growing regions will become available further from the equator. For Arabica coffee, the countries with the most new coffee regions are Brazil, Mexico, and Angola. While many countries will gain new suitable land, globally this is only be 10 - 20% of what may be lost (3.7).

Introduction

Coffee plays a vital role in many countries, providing livelihoods to 25 million inhabitants of tropical countries and supporting a $81 billion industry (Sharf, 2014), making it one of the most valuable commodities in the world. However, coffee is extremely vulnerable to climate change. Already changes in climate are making disease outbreaks more common and shifting suitable growing regions (Guilford, 2014; Malkin, 2014). The coffee industry consists of a complex web of small-holder farmers, multinational corporations, government policies, and diverse consumers. As coffee demand continues to expand, the international coffee system will respond to pressure from all of these elements.

This research studies the effects of climate change on coffee from a global perspective. As productive coffee regions shift, every aspect of the coffee system will be impacted, from developing country farmers to developed country consumers. By 2050, these long-term shifts will reshape the global coffee market.

The effects of climate on coffee also include shorter timescales. Decadal and interannual climate cycles have long impacted coffee production worldwide. Production in different regions varies in their degree of sensitivity to current climate variability and increasingly extreme temperatures. Understanding these differences is an important input to global planning.

Coffee production has considerable potential for supporting sustainability and economic opportunities for the future, but planning requires a better understanding of the interconnections between production, trade, and the environment. The future of coffee depends on understanding the risks, instituting high-resolution monitoring, and acting in anticipation of future impacts. In this report, we have emphasized new research and reanalyses, rather than reviews of existing knowledge. We build upon the strong foundation laid by recent articles and reports. In particular, a recent report by *coffee&climate* (2015) addresses the challenge that climate poses to coffee farmers and presents an approach to adaptation planning. The International Coffee Organization (ICO) has produced a report detailing the modes of climate impacts on coffee and projects aimed at addressing them (ming). The chapters list many additional references.

Throughout this report, we take a quantitative, empirical approach to questions about the current and future state of the global coffee system. We identify relationships that are closely tied to the physical world, drawing on the strengths of the Earth Institute. Furthermore, the relationships we study are as they are reflected in aggregated data, often at the country-wide level. There are important impacts of climate change on farms and farmers that only appear implicitly in this data and our results.

We emphasize a number of elements underrepresented in the coffee literature. First, we focus on the pervasive uncertainty underlying coffee and climate analyses. This stems from a combination of the inherent variability of climate, the heterogeneity of coffee farming practices, and uncertainty in the statistical results relating them. Without this, the true risk of climate change to coffee can both be misestimated and misattributed. We have incorporated the analysis of uncertainty throughout our work.

Second, and related to this, is the state of coffee production knowledge. Coffee data is often not available at high resolution and not available comprehensively within regions. It is also likely to have considerable bias, since coffee production is highly politicized in many countries. We have developed a new spatial coffee production database to address these problems, and emphasize statistical techniques and tools that account for the erratic data quality.

Third, we have drawn from multiple academic literatures to apply innovative approaches to questions around coffee and climate. These include our Bayesian approach to estimating suitability; our study of interactions between multiple signals to understand variability; and our use of the most robust methods of econometrics to study production.

For future climate and suitability projections, we target the year 2050. Much of the climate change that will occur by 2050 is a result of emissions which have already occurred. These thirty-five years will be instrumental to the future of coffee, as we learn to adapt to rapid climate change.

By 2050, if the international community has not enacted strong, effective carbon controls, the rate of warming will be even greater. 2050 could be the beginning of additional, catastrophic climate impacts on coffee and elsewhere. However, this year provides a useful road mark, far enough into the future to see the impacts but close enough that planning for those impacts can start now. In this report, we distinguish between the effects of climate on coffee across different "time scales". The nature of climate impacts, and the appropriate methods for analysis, differ for different scales. To understand these differences, it is important to understand the difference between weather and climate.

"Weather" describes the actual temperature, rainfall, and other atmospheric features that we observe. Weather is constantly changing, even when climate is not changing. "Climate" is traditionally defined as the 30-year average of weather (**?**). When coffee plants wilt because of low rainfall, they are responding to weather, and we can study those responses irrespective of changes in climate. When coffee can no longer be productively grown in an area because droughts are too frequent, this is a response to climate (even though it is mediated by individual weather events).

A third time scale for understanding climate impacts lies between daily weather and 30-year averaged climate. The climate goes through natural cycles that can last many years. For example, the El Niño / La Niña cycle lasts 2 to 7 years, and has a large impact on seasonal weather. Other climate cycles are called "decadal" or "multidecadal", because they can persist in one state for over 10 years, such as the currently high temperatures in the northern Atlantic ocean.

To understand the effects of weather, we study how year-to-year changes in yield are driven by the patterns daily weather observed during each year (see chapter **??**). Most year-to-year changes in yields are the result of variability in weather. We can look at historical weather and historical changes in yields as a way to predict how coffee will respond in the future under hotter temperatures.

We study multi-year climate cycles, including both El Niño and multidecadal cycles, in a second analysis (see chapter **??**). As with other aspects of climate, the impacts of these cycles occur through their effects on local weather, but they reveal their secrets better when studied globally and over many years.

Finally, to understand the effects of climate, we perform a suitability analysis (see chapter **??**). Long-term trends will shift the suitable regions for coffee, and we study these impacts distinctly from those that determine yields. Our model of coffee suitability is based on the pattern of current coffee cultivation, rather than yields as with the previous two analyses. We then apply this model of suitability to future climate to determine where coffee will be able to be productively grown.

This report is organized into multiple chapters, exploring different aspects of the climate-coffee connection.

- **Chapter 1** discusses the state of knowledge and uncertainty about climate change in the coffee belt.
- **Chapter 2** presents the new database of coffee production for studying climate impacts.
- **Chapter 3** presents a new approach to suitability and the changes we predict under the future climate.
- **Chapter 4** studies the El Niño / La Niña cycle and other climate signals of internal variability.
- **Chapter 5** builds a robust and multi-level model of coffee production based on weather variation.
- **Chapter 6** discusses our results for the global coffee market and the effect of production on prices.

- **Chapter 7** provides some thoughts on the future of coffee and coffee research.

A number of additional analyses are reported in Appendix A, many of which offer avenues for future research. Appendix B describes the coffee production database we generated and the principles behind it. Appendix C provides documentation for decision-support tools that we have generated in the course of our research.

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