The Future of Coffee Production in a Changing Climate – Will Demand Outpace Supply?

Garrett Corwin, MEM
Phoenix Feng, MEM
Sara Naghavi, MEM
Molly Johnson, MEM/MBA

Advisor: Joe Bachman
In Collaboration with Conservation International

Master's project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment of Duke University

Table of Contents

I. Abstract

The coffee sector is valued at $102 billion, but its future growth is at risk of a supply deficit due to climate change. Conservation International (CI) is a global environmental nonprofit organization dedicated to preserving forested and protected land from future coffee expansion. To achieve CI's goal, a methodology was developed to project coffee supply into 2050, considering changing bioclimatic and social conditions for Brazil and Vietnam's coffee industries. Estimated supply was forecasted based on quantifiable variables. For variables that were only qualifiable, their influence on production was analyzed using magnitude and direction. Results show numerous bioclimatic and social parameters negatively affect coffee production, the most profound being increases in atmospheric temperature. Our work will continue to be augmented with additional research to understand the interaction and quantifiable effects of these variables on future production and forest/protected land encroachment. This project additionally outlines high-level management and investment recommendations to incentivize industry action.

II. Executive Summary

Despite an increasing trend in global coffee consumption (demand), coffee production (supply) is anticipated to decrease due to climate change. Conservation International (CI), a global environmental non-governmental organization, aims to protect and conserve forested land by proactively aiding corporations in reducing their supply chain risk. CI co-founded the Sustainable Coffee Challenge (SCC) – a joint task force between public and private industries – with the goal to make coffee a 100% sustainable agricultural product. This will be achieved when all coffee produced meets the sustainable practices of improving the livelihoods for all coffee workers, tripling productivity on existing farmland and preventing deforestation. This master's project supported the SCC goal by working with CI to develop a methodology and model to project future coffee production to identify where and when risk to supply may occur and to explore potential management and investment recommendations to reduce this risk.

Coffee is a global, agricultural commodity grown primarily by small farmers. The two main cultivars are Arabica (*Coffea arabica*) and Robusta (*Coffea canephora*). Coffee production and its associated market pricing is influenced by both bioclimatic and economic parameters.

The model created for this project builds upon CI's earlier work of projecting potential demand and developing a GIS analysis of suitable land to produce Arabica and Robusta. The GIS mapping determined the change in land area where each cultivar could be grown until 2050. This mapping guides the starting point for our model.

The model begins with an upper supply volume boundary created using the potential suitable land and yield data. It then removes supply volume due to impacts from bioclimatic and social parameters to create the supply projection. These estimates may then be compared to demand estimates to gauge the potential gaps and surpluses. Forested and protected land at risk is incorporated to determine the potential encroachment on this area to meet coffee demand. Given the challenge of quantifying several parameters due to insufficient data, a qualitative methodology based on published literature was used to guide the model and supplement quantitative output. The research helped determine the direction of the impact (positive or negative) and its strength (relative impact on production). With further targeted research, these qualitative parameters may become quantifiable with potential to improve the model and the projections of coffee supply.

Brazil and Vietnam, leading producers of Arabica and Robusta, respectively, served as case studies of Arabica and Robusta supply, respectively. Land encroachment, temperature change, and pest and fungal diseases will all negatively impact future coffee supply. Arabica production is particularly prone to pests and fungal diseases, whereas Robusta production is more susceptible to temperature changes. Brazil's Arabica could lose 65% of potential suitable productive land and Vietnam's Robusta 45% between 2010 and 2050. Increasing temperatures from climate change could cause each cultivar's production to drop by over 20%. Pests and fungal disease could reduce Brazil's Arabica yields by 30% to 50% and Vietnam's Robusta yields by 15%.

Through its SCC initiative, CI can promote best practices for coffee production to mitigate the adverse impacts of climate change thereby lowering the risk of a coffee shortage and preventing encroachment on forested land. Using existing data, CI can emphasize parameters with the highest likelihood and forcefulness in causing a significant supply disruption to channel their corporate partner's efforts. Finally, this project positions CI to work with partner organizations to lever tools and knowledge to improve the model.

III. Introduction

a. Background

Coffee is a tropical crop that is processed into a hot beverage and widely consumed around the world, with nearly 500 billion cups brewed globally each year[1]. The two primary species, Arabica (*Coffea arabica*) and Robusta (*Coffea canephora*), account for nearly 70% and 30% of the global coffee production, respectively[2]. Per country coffee production fluctuates yearly based on market, social, and biotic conditions. Specifically, climate change is expected to have substantial impacts on the coffee production[3] as changes in temperature, precipitation, pests, and diseases[4], all influence coffee growth and yield.

Demand for coffee is anticipated to triple by 2050, growing by ~2% annually, while suitable land for coffee cultivation is predicted to diminish drastically due to changing climate conditions. It is anticipated that by 2050, the demand for coffee will increase, while suitable land and real output will decrease due to changing climate conditions.

As part of our degree requirement to earn a Master of Environmental Management degree from the Nicholas School of the Environment at Duke, we have completed a client-based master's project with Conservation International (CI). The objective of this project was to develop a methodology to project the future supply of coffee into 2050 and to apply this methodology to calculate global and country-level projections. If supply gap exists, and other regions can supplement the production to narrow the gap, the ultimate goal may be to encourage supply chain investments by CI's corporate and government partners. Our report focuses on Brazil's Arabica production and Vietnam's Robusta production to develop a methodology to forecast coffee supply into 2050.

---

[1] *Coffee Statistics in 2021: Consumption Trends & Industry Data*. (n.d.). Much Needed. Retrieved March 23, 2021, from https://muchneeded.com/coffee-consumption-statistics/

[2] Conservation International. (2015). Coffee in the 21st Century: Will Climate Change and Increased Demand Lead to New Deforestation?. Retrieved from: https://www.conservation.org/docs/default-source/publication-pdfs/ci-coffee-report.pdf

[3] Bunn, C., Läderach, P., Ovalle Rivera, O., & Kirschke, D. (2015). A bitter cup: climate change profile of global production of Arabica and Robusta coffee. Climate Change, 129: 89–101.

[4] Jaramillo, J., Muchugu, E., Vega, F., Davis, A., Borgemeister, C., & Chabi-Olaye, A. (2011). Some like it hot: the influence and implications of climate change on coffee berry borer (Hypothenemus hampei) and coffee production in East Africa. PLoS One 6 (9), e24528. http://dx.doi.org/10.1371/journal.pone.0024528.

b. Conservation International and the Sustainable Coffee Challenge

Conservation International is a multinational environmental non-governmental organization (ENGO) headquartered in Arlington, VA. With offices in more than 24 countries and with a measurable impact in more than 70 countries, CI is dedicated to "spotlighting and securing the critical benefits that nature provides to humanity" since 1987.[5]

Conservation International's interest in coffee production stems from its mission statement and partnerships with governments and industry groups. Through its founding and partnership of in the Sustainable Coffee Challenge (SCC) during the 2015 Paris Climate Accord summit, Conservation International intends to influence the prioritization of sustainable coffee products that positively impact coffee farmers and their communities. The SCC brings together a broad range of coffee stakeholders from large for-profit companies to research institutions and non-governmental organizations (NGO). Most consumer-packaged goods companies purchase their product through distributors, so comprehending supply issues from the beginning of the value chain is an involved and opaque process. The SCC partners set transparent commitments around sustainable agriculture practices, deforestation, and improving the lives of coffee farmers[6]. The initiative of 163 partners aims "to make coffee the world's first sustainable agricultural product," through precompetitive collaboration of industry and government-level solutions for all components of the coffee value chain[7]. Conservation International's individual commitment to the Challenge has resulted in a "25% increase in demand for sustainable coffee and sparked new commitments, collaborations and investments that support the transition of 75% of the sector to sustainable production."[8] Additionally, because Conservation International is invested in conserving the integrity of as much land in its natural state, there is incentive to empower and enable farmers on their current land to not expand production into forested and protected areas[9].

c. Project Objective and Challenges

Our client, Conservation International, aims to quantify the impact of climate change on coffee production in order to incentivize corporate and national commitments to limit and lower the coffee value chain footprint. Additionally, they are motivated to incentivize investment in measures that best ensure continued supply of this commodity into 2050 and prevent production encroachment into forested or protected lands. This goal aligns with consumers' expectations of increased traceability, transparency, and Environmental, Social, and Corporate Governance (ESG)[10].

Several studies describe the impact of changing climate conditions on coffee production, though these studies focus on introducing this matter, rather than building out concrete and actionable evaluations. This literature includes case studies of location or species-specific work and field or lab experiments and is highlighted in the discussion section of this report. These publications have additionally influenced our management section at the conclusion of this report.

---

[5] *Conservation International*. (n.d.). Retrieved March 11, 2021, from https://www.conservation.org/home

[6] *Homepage*. (n.d.). Retrieved April 21, 2021, from https://www.sustaincoffee.org/

[7] *Partners—Sustainable Coffee Challenge*. (n.d.). Retrieved April 21, 2021, from https://www.sustaincoffee.org/partners/

[8] *Partner Profile: Conservation International*. (n.d.). Retrieved April 21, 2021, from https://www.sustaincoffee.org/partners/conservation-international

[9] Conservation International. (2015). Coffee in the 21st Century: Will Climate Change and Increased Demand Lead to New Deforestation?. Retrieved from: https://www.conservation.org/docs/default-source/publication-pdfs/ci-coffee-report.pdf

[10] *Larry Fink's Letter to CEOs*. (n.d.). BlackRock. Retrieved April 21, 2021, from https://www.blackrock.com/corporate/investor-relations/2020-larry-fink-ceo-letter

Prior to this investigation, Conservation International has developed demand predictions for global coffee consumption, utilizing historic consumption data and trend calculations. Demand calculations incorporate population growth and the market expansion of specific products as economies continue to grow; these variables are both fairly easy to quantify and publicly available. Compared to demand projections, supply is a much more complicated calculation. It is important to project supply into the future in order to match up supply and demand projections and comprehend potential supply gaps, which lead to price fluctuations and unsatisfied demand. The demand for coffee is largely inelastic so even when cost is passed onto consumers, they are unlikely change their consumption habits. Supply, however, is more elastic. Farmers, if they lose money continually, will look elsewhere for opportunities. Farmers aim to produce a steady supply year after year but micro and macro conditions arise, decimating both individual and country wide production. In an ideal scenario, supply forecasts could be calculated by taking the expected yield per acre and multiplying it by the total acreage. However, significant crop disturbances like pests or unfavorable weather that must be taken into consideration. Supply calculations for coffee and other crop commodities are complex as these production factors may be unknown or lack sufficient data to be quantified. In particular, integrating anticipated climate factors into supply projections is challenging, as these factors interact with one another to amplify or dampen their effects, making concrete implications on coffee production difficult to predict.

For this project, we developed and applied a methodology to forecast coffee supply into 2050 on Brazil's Arabica and Vietnam's Robusta production. Detailed climate change affected supply projections are difficult because the inputs are not as well studied and are harder to quantify for reasons described. Our quantitative analysis model is therefore limited to bioclimatic analysis of temperature, pest, and land analysis. Qualitative analysis was conducted on the remaining social and market parameters, as well as bioclimatic parameters where data was missing or unavailable. Our analyses provide a direction for CI to continue this quantitative work to calculate if supply will fall short of demand into 2050. We outline that the disruption these conditions cause on coffee production can be lessened through management practices. We further highlight these management approaches, as we believe through investments by corporate and national partners, may better ensure steady supply of coffee into the future.

Ultimately, this report aims to illuminate the challenges coffee farmers face and their relative impact on coffee production. The analyses targeted on the countries that make up 80% of coffee production, which include: Brazil, Colombia, Honduras, Ethiopia, India, Indonesia, and Vietnam. This report will first go through a high-level overview of factors that influence coffee production and then through the work Conservation International has completed. We then discuss how this work was built upon in the quantitative and qualitative methodologies. Finally, the report outlines the results analyses conducted of Brazil and Vietnam, the top Arabica and top Robusta producing countries. This report concludes with recommendations and closing remarks.

IV. Coffee Background

a. Coffee Value Chain

The coffee value chain is composed of five main stages (Figure 1): growing, exporting, roasting, distribution, and retail consumption. Coffee cultivation activities include pruning, weeding, irrigation and fertilizer application, and then coffee cherries are harvested manually or mechanically[11]. Farmers will remove the central coffee bean either before or after processing. Under dry processing, the intact coffee cherry is dried, and then the bean is removed. Under wet processing, the freshly picked cherry is de-pulped and the bean is removed immediately for drying[12]. Harvesting and processing can happen on the same farm, or separately by different entities in the supply chain. After post-harvest processing, the coffee is considered 'green coffee.' Green coffee is often aggregated by local co-ops and private traders. The harvest is then sold to exporters who may or may not work with a trading house to connect with roasters in the importing country. Finally, roasting and wholesale or retail consumption can occur at the same facility, or a roaster will process the green coffee, and then sell it to a retail outlet[13] . This is where the most value is added in the value chain[14]. Overall, there is a large power imbalance between purchases in the northern hemisphere and producers in the southern hemisphere[15].

---

[11] Luna, Fatima & Wilson, Paul. (2015). An Economic Exploration of Smallholder Value Chains: Coffee Transactions in Chiapas, Mexico. International Food and Agribusiness Management Association. 18.

[12] Coffee, H. (n.d.). *Coffee Processing Methods: Dry Vs. Wet*. Hayman Coffee. Retrieved April 21, 2021, from https://www.haymancoffee.com/blogs/coffee-blog/coffee-processing-methods-dry-vs-wet

[13]Hutson, C. (2017, September 9). From Bean to Cup: How the Coffee Supply Chain Works | Atlas Coffee Club. *Atlas Coffee Club Blog | Club Culture*. https://club.atlascoffeeclub.com/coffee-supply-chain/

[14] Luna, Fatima & Wilson, Paul. (2015). An Economic Exploration of Smallholder Value Chains: Coffee Transactions in Chiapas, Mexico. International Food and Agribusiness Management Association. 18.

[15] Grabs, J., & Ponte, S. (2019). The evolution of power in the global coffee value chain and production network. *Journal of Economic Geography*, *19*(4), 803–828. https://doi.org/10.1093/jeg/lbz008

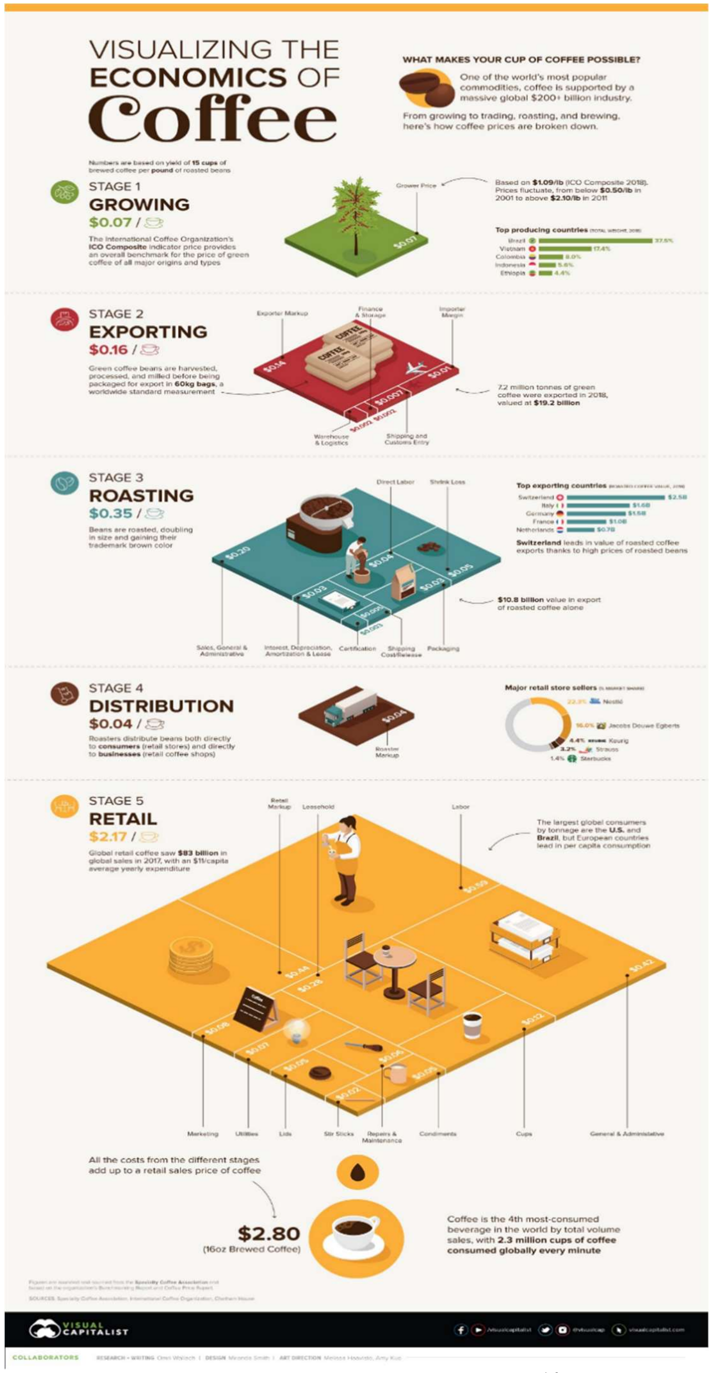

Figure 1. Value Chain Visualization[16]

[16] Wallach, O. (2020, October 24). The Economics of Coffee in One Chart. *Visual Capitalist*. https://www.visualcapitalist.com/the-economics-of-coffee-in-one-chart/

b. Market

Coffee is the fourth most traded commodity globally with 2.4 million 60kg bags imported globally in 2019[17] [18]. The coffee market is very competitive - the top players in the industry are: The Kraft Heinz Company, Starbucks Coffee Company, The J.M Smucker Company, Luigi Lavazza SPA, Nestle SA, The Coca-Cola Company, JAB Holding Company, and Tata Global Beverages,[19] along with hundreds of smaller companies along the value chain.

The global coffee market was valued at $102.15 billion in 2019, and it's expected to grow to $155.64 billion by 2026[20]. This increase is primarily the result of coffee becoming a staple in new countries[21]. Coffee's closest substitute is tea which is in higher demand and consumed more than coffee on a volume basis. However, as countries like China and India develop and their residents have more disposable income, there is a tendency to transition from being primarily tea drinkers to being primarily coffee drinkers [22] [23] [24].

c. Production

i. GDP and National Economies

Coffee plays an important role in supporting the national gross domestic product (GDP) of the top seven coffee producing countries, particularly for those reliant on export earnings.[25] Figure 2 provides a breakdown of the top producing countries and how much coffee contributes to their GDP and coffee export values.

Country	% of total coffee production	Coffee Exports ($ billion)	2019 GDP ($ billion)	% coffee of GDP	2019 Total product exports ($ billion)	% coffee of exports
Brazil	36.81	4.58	1840	0.25	230.00	2.00
Vietnam	18.24	2.22	260	0.85	280.00	0.80
Colombia	8.11	2.60	320	0.80	40.50	6.40
Honduras	4.29	0.96	30	3.81	7.80	12.30
Indonesia	5.51	0.88	1120	0.08	186.00	0.50
Ethiopia	4.55	0.84	960	0.87	3.11	26.90
India	3.10	0.72	2870	0.02	330.00	0.20

*As of 2019

Figure 2. 2019 GDP and Coffee Export Value Information by Country, arranged by contribution to coffee market [26, 27, 28]

[17] Luna, Fatima & Wilson, Paul. (2015). An Economic Exploration of Smallholder Value Chains: Coffee Transactions in Chiapas, Mexico. International Food and Agribusiness Management Association. 18.

[18] United States Department of Agriculture. (2020). Coffee: World Markets and Trade. Retrieved: April 21, 2021. https://apps.fas.usda.gov/psdonline/circulars/coffee.pdf

[19] *Global Coffee Market | Growth | Trends | Forecast*. (n.d.). Retrieved March 11, 2021, from https://www.mordorintelligence.com/industry-reports/coffee-market

[20] *Global Coffee Market (2020 to 2026)—Industry Perspective, Comprehensive Analysis and Forecast—ResearchAndMarkets.com*. (2020, October 6). https://www.businesswire.com/news/home/20201006005799/en/Global-Coffee-Market-2020-to-2026---Industry-Perspective-Comprehensive-Analysis-and-Forecast---ResearchAndMarkets.com

[21] *Global Coffee Market | Growth | Trends | Forecast*. (n.d.). Retrieved March 11, 2021, from https://www.mordorintelligence.com/industry-reports/coffee-market

[22] *Coffee Market—Growth | Trends | Forecast (2021—2026)*. (n.d.). Retrieved April 21, 2021, from https://www.mordorintelligence.com/industry-reports/coffee-market

[23] *Global Coffee Market (2020 to 2026)—Industry Perspective, Comprehensive Analysis and Forecast—ResearchAndMarkets.com*. (2020, October 6). https://www.businesswire.com/news/home/20201006005799/en/Global-Coffee-Market-2020-to-2026---Industry-Perspective-Comprehensive-Analysis-and-Forecast---ResearchAndMarkets.com

[24] *Global Coffee Market (Value, Volume) Analysis Report 2021*, 2021, https://www.businesswire.com/news/home/20210210005386/en/Global-Coffee-Market-Value-Volume-Analysis-Report-2021-Market-Insights-COVID-19-Impact-Competition-and-Forecast-to-2026---ResearchAndMarkets.com

[25] Seudieu, D. (2015). Developing a Sustainable Coffee Economy. International Coffee Organization, Mumbai.

[26] OEC - The Observatory of Economic Complexity. (n.d.). Retrieved March 21, 2021, from https://oec.world/en

[27] Statista—The Statistics Portal. (n.d.). Statista. Retrieved March 21, 2021, from https://www.statista.com/

[28] World Bank Open Data | Data. (n.d.). Retrieved March 21, 2021, from https://data.worldbank.org/

ii. Labor, Livelihoods, and Smallholder Farms

The coffee industry provides a primary income for 25 million smallholder farmers and farm workers[29] who are collectively responsible for producing about 80% of the world's coffee supply[30]. Based on the state of the market, it can be incredibly difficult for smallholder farmers to make a living from coffee alone.[31].

With such small profit margins, it can be hard for smallholder farmers to save money to survive low periods in the market or invest in long-term strategies and infrastructure. Ha et al. (2008) studied a major coffee producing region of Vietnam and found that a farmer's initial reaction to poor market conditions was to limit the amount of fertilizer they applied. Limiting this input lowers their growing costs and could help maintain their profit margin. However, long term, smallholder farmers will make moves to diversify their risk. The study found that between 1999-2003, which included three years of low prices, the proportion of households with three or more crops doubled and off-farm employment went from 13% to 43%[32]. The natural reaction was not to leave the coffee industry entirely, but to not depend on it as their sole source of income. The author's found that income derived from coffee also fell from 87% to 77%[33].

Smallholder farmers are becoming increasingly involved in contract farming, which obligates the coffee farmers to sell their beans to a specific agro-industrial firm. This guarantees a predictable supply for the firm, and the farmer receives capital, infrastructure, and access to the global market[34]. With this type of relationship, the firm can dictate certain standards and parameters, such as the quantity they expect to receive and the quality of the beans. However, these contracts can fail to recognize the inherent variability of dealing with coffee plants. Though there are numerous models of contract farming, the asymmetric dependence of farmers on companies creates a vulnerable and unsustainable relationship.[35] Contract farming can benefit small farms by coordinating production and distribution, but it can also result in an overdependence on external players with asymmetric information and power[36].

d. Cultivars

Arabica and Robusta are the dominant coffee varieties on the market, and Arabica production is roughly triple that of Robusta. Arabica is a higher quality, more mild tasting coffee than Robusta. Robusta more common in instant coffee, it has a bitter flavor, and higher caffeine

[29] Luna, Fatima & Wilson, Paul. (2015). An Economic Exploration of Smallholder Value Chains: Coffee Transactions in Chiapas, Mexico. International Food and Agribusiness Management Association. 18(3)

[30] *Farmer Profitability: Managing Risk in the Supply Chain | Specialty Coffee Association News*. (n.d.). Retrieved April 21, 2021, from https://scanews.coffee/2015/08/04/farmer-profitability-managing-risk-in-the-supply-chain/

[31] *Farmer Profitability: Managing Risk in the Supply Chain | Specialty Coffee Association News*. (n.d.). Retrieved April 21, 2021, from https://scanews.coffee/2015/08/04/farmer-profitability-managing-risk-in-the-supply-chain/

[32] Ha, D.T., & Shively, G. (2008). Coffee Boom, Coffee Bust and Smallholder Response in Vietnam's Central Highlands. *Review of Development Economics,* 12(2): 312-326. Retrieved from: https://doi-org.proxy.lib.duke.edu/10.1111/j.1467-9361.2007.00391.x

[33] Ha, D.T., & Shively, G. (2008). Coffee Boom, Coffee Bust and Smallholder Response in Vietnam's Central Highlands. *Review of Development Economics,* 12(2): 312-326. Retrieved from: https://doi-org.proxy.lib.duke.edu/10.1111/j.1467-9361.2007.00391.x

[34] Anh, N.H., Bokelmann, W., Thuan, N.T., Nga, D.T., Minh, N.V. (2007). Smallholders' Preferences for Different Contract Farming Models: Empirical Evidence from Sustainable Certified Coffee Production in Vietnam. MDPI, Open Access Journal, 11(14): 1-26.

[35] Hung Anh, N., Bokelmann, W., Thi Thuan, N., Thi Nga, D., & Van Minh, N. (2019). Smallholders' Preferences for Different Contract Farming Models: Empirical Evidence from Sustainable Certified Coffee Production in Vietnam. *Sustainability*, *11*(14), 3799. https://doi.org/10.3390/su11143799

[36] Hung Anh, N., Bokelmann, W., Thi Thuan, N., Thi Nga, D., & Van Minh, N. (2019). Smallholders' Preferences for Different Contract Farming Models: Empirical Evidence from Sustainable Certified Coffee Production in Vietnam. *Sustainability*, *11*(14), 3799. https://doi.org/10.3390/su11143799

content. Robusta is cheaper than Arabica because of its less desire taste and because it's an easier variety to grow[37].

Arabica is native to Ethiopia, but was first cultivated in Yemen where it then spread to India and Indonesia. Two Arabica varieties immerged from this migration - Bourbon and Typica. Bourbon plants yield more coffee than Typica but are more sensitive to harsh weather[38]. They are both highly susceptible to coffee diseases, which makes their survival dependent on a farmer's ability to protect them from disease spread[39]. Southeast Asian Robusta, which accounts for 55% of Robusta on the market, originated in the Congo basin[40]. Robusta is a more tolerant variety than Arabica, which is why it could fill any potential supply gaps in the coffee market caused by climate variability[41]. Hybrids of both Arabica and Robusta are vital because they can maintain a higher quality flavor while also being more resistant to disease, high temperatures, and drought[42],[43].

e. Bio-Climactic Growth Attributes

Coffee is grown in a region of the world called the Coffee Belt, which includes the tropics and sub-tropics[44]. In most producing countries, there will be some overlap in suitable area for both Arabica and Robusta coffee cultivation, though the cultivars generally grow in distinct locations. The plants live for decades, with different growth and flowering patterns depending on climate[45]. Its production cycle spans from flowering to harvest, and is greatly affected by climate variations. Robusta coffee bean size is at least partially determined by bioclimatic factors, including temperature and rainfall. During flowering, high temperatures and less rainfall is most favorable for optimal production, while lower temperatures and high rainfall are most optimal during the growing stage[46].

i. Temperature

Arabica has an optimal growing temperature between 16 and 24-degrees Celsius[47]. Robusta has been deemed a more robust coffee species than Arabica, and thus more posed to tolerate changing climate conditions. Recent studies, however, delineate its optimal temperatures as lower than previously estimated, and find that the species is less resistant to coffee destroying fungi than previously assumed[48]. It is now understood that Robusta performs optimally below

---

[37] Pack, T. R. (2014). *10 differences Between Robusta & Arabica Coffee*. The Roasters Pack. Retrieved March 11, 2021, from https://theroasterspack.com/blogs/news/15409365-10-differences-between-robusta-arabica-coffee

[38] *The Beginner's Guide To Coffee Varieties*. (n.d.). JavaPresse Coffee Company. Retrieved March 11, 2021, from www.javapresse.com

[39] *Arabica Coffee Varieties | Main Variety Types*. (n.d.). Retrieved March 11, 2021, from https://varieties.worldcoffeeresearch.org

[40] Kath, J, Byrareddy, VM, Craparo, A, et al. Not so robust: Robusta coffee production is highly sensitive to temperature. *Glob Change Biol*. 2020; 26: 3677– 3688. https://doi.org/10.1111/gcb.15097

[41]Kath, J, Byrareddy, VM, Craparo, A, et al. Not so robust: Robusta coffee production is highly sensitive to temperature. *Glob Change Biol*. 2020; 26: 3677– 3688. https://doi.org/10.1111/gcb.15097

[42] Kath, J, Byrareddy, VM, Craparo, A, et al. Not so robust: Robusta coffee production is highly sensitive to temperature. *Glob Change Biol*. 2020; 26: 3677– 3688. https://doi.org/10.1111/gcb.15097

[43]Kath, J, Byrareddy, VM, Craparo, A, et al. Not so robust: Robusta coffee production is highly sensitive to temperature. *Glob Change Biol*. 2020; 26: 3677– 3688. https://doi.org/10.1111/gcb.15097

[44] *National Coffee Association USA > About Coffee > Coffee Around the World*. (n.d.). Retrieved March 11, 2021, from https://www.ncausa.org/About-Coffee/Coffee-Around-the-World

[45] Iscaro, J. (2014). The Impact of Climate Change on Coffee Production in Colombia and Ethiopia. Global Majority E-Journal, 5(1): 33-43. Retrieved from: http://www.bangladeshstudies.org/files/Global_Majority_e_Journal_5_1.pdf#page=33

[46] Kath, J., Byrareddy, V. M., Mushtaq, V., Craparo, A., & Mario, P. (2021). Temperature and rainfall impacts on robusta coffee bean characteristics. Climate Risk Management, 32. Retrieved from: https://doi.org/10.1016/j.crm.2021.100281

[47] *Coffee Environment: Climate Conditions for Growing Coffee Beans*. (n.d.). Retrieved March 11, 2021, from http://www.coffeeresearch.org/agriculture/environment.htm

[48] Dzombak, R. (2020). *Coffee's robust back-up bean isn't as resistant to climate change as once thought*. Massive Science. Retrieved March 11, 2021, from https://massivesci.com/articles/coffee-climate-change-robusta-arabica-temperature-hot-cold/

20.5-degrees Celsius, tolerating an average range of 16.2 to 24.1-degrees Celsius. For both cultivars, temperature changes beyond this range result in coffee yield losses. For Robusta, every 1-degree Celsius increase in temperature above its range results in a 14% decline in yield, with a linear relationship of yield reduction as temperature increases beyond this span[49].

For Robusta, higher temperatures during growth and harvest results in premature berry ripening, as well as mold activity, and thus significant bean damage. Excessive heat during cherry formation leads to stunted growth and underdeveloped beans. During bean development and ripening, high temperatures also result in smaller beans, as they do not get fully filled. Increases in temperature are, however, also related to increases in coffee berry borer and other pest reproduction rates. At optimal growing temperatures of 27.5 degrees Celsius, pest populations are denser and more prevalent, contributing to increased harvest damage[50]. However, high temperatures coupled with different moisture conditions, yield different outcomes. This and coffee bean responses to cooler temperatures will be discussed in the following section.

ii. Precipitation

Coffee grows best with well demarcated wet and dry periods throughout the year. Climate change can negatively impact coffee production because having too much or not enough water at the right time can hinder plant development. For example, water stress at the wrong time will hinder bean development, but water stress at the right time can improve yields by inducing crop flowering[51]. Excessive rain can also encourage fungus and mold growth, increase erosion, and damage the flowers[52] [53]. Distinct wet and dry periods also signal to the plant that one harvest season is ending and the next development period should begin[54].

Changes in bioclimatic parameters, such as temperature and precipitation, don't happen in isolation – the atmospheric temperature could increase and the precipitation volume could decrease in the same growing season. Different combinations of these bioclimatic changes will impact coffee development in different ways. For example, during the flower period, less rainfall and higher temperatures are desirable because it can increase bean size, but higher rainfall and lower temperatures will do the opposite[55] [56]. Overall, precipitation changes will impact areas differently depending on if they experience one or multiple harvests per year[57]. For example, increases in precipitation have positive yield outcomes in many producing areas in Africa[58].

---

[49]Kath, J, Byrareddy, VM, Craparo, A, et al. Not so robust: Robusta coffee production is highly sensitive to temperature. *Glob Change Biol*. 2020; 26: 3677– 3688. https://doi.org/10.1111/gcb.15097

[50] Kath, J., Byrareddy, V. M., Mushtaq, V., Craparo, A., & Mario, P. (2021). Temperature and rainfall impacts on robusta coffee bean characteristics. Climate Risk Management, 32. Retrieved from: https://doi.org/10.1016/j.crm.2021.100281

[51] Kath, J., Byrareddy, V. M., Mushtaq, V., Craparo, A., & Mario, P. (2021). Temperature and rainfall impacts on robusta coffee bean characteristics. Climate Risk Management, 32. Retrieved from: https://doi.org/10.1016/j.crm.2021.100281

[52] *How Does Rain Affect Coffee?* (n.d.). Big Island Coffee Roasters. Retrieved March 11, 2021, from https://bigislandcoffeeroasters.com/blogs/blog/how-does-rain-affect-coffee

[53] Adhikari, U., Nejadhashemi, A.p., & Woznicki, S.A. (2015). Climate change and eastern Africa: a review of impact on major crops. *Food and Energy Security* 2015; 4(2): 110– 132. Retrieved from: https://onlinelibrary.wiley.com/doi/full/10.1002/fes3.61

[54] *How Does Rain Affect Coffee?* (n.d.). Big Island Coffee Roasters. Retrieved March 11, 2021, from https://bigislandcoffeeroasters.com/blogs/blog/how-does-rain-affect-coffee

[55]Kath, J., Byrareddy, V. M., Mushtaq, V., Craparo, A., & Mario, P. (2021). Temperature and rainfall impacts on robusta coffee bean characteristics. Climate Risk Management, 32. Retrieved from: https://doi.org/10.1016/j.crm.2021.100281

[56]Kath, J, Byrareddy, V.M., Craparo, A, et al. (2020). Not so robust: Robusta coffee production is highly sensitive to temperature. *Glob Change Biol*. 26: 3677– 3688. Retrieved from: https://doi.org/10.1111/gcb.15097

[57]Jaramillo, J., Chabi-Olaye, A., Kamonjo, C., et al. (2009). Thermal Tolerance of the Coffee Berry Borer *Hypothenemus hampei*: Predictions of Climate Change Impact on a Tropical Insect Pest. *PLoS ONE,* 4(8): e6487.

[58] Adhikari, U., Nejadhashemi, A.p., & Woznicki, S.A. (2015). Climate change and eastern Africa: a review of impact on major crops. *Food and Energy Security* 2015; 4(2): 110– 132. Retrieved from: https://onlinelibrary.wiley.com/doi/full/10.1002/fes3.61

iii. Humidity

The fungus called 'coffee leaf rust' (CLR) flourishes in areas where there is moisture in the air, a condition that is important for plant hydration and can happen for many reasons. [59]. Humidity has consequences after harvest when the coffee is processed and stored. During cherry drying, the humidity can cause mold development and negatively impact overall yield[60]. Without humidity, however, the beans risk drying out too much[61].

iv. Altitude

Altitude influences the taste of coffee through the increased physiological work within coffee beans at higher elevation. Arabica has optimal growth between 1,800 and 6,300 feet depending on where the area sits latitudinally. Robusta sits much lower and is grown between sea level and 3,000 feet[62]. The hardness of the coffee bean increases as elevation increases. Similar to how humans who ascend to higher elevation have difficulty breathing, it also becomes harder for coffee beans to develop at these altitudes, resulting in slower and denser bean growth. The denser the bean, the more it is desired - the sugars become more concentrated and the beans are more acidic, which results in a more flavorful cup of coffee.[63]

V. Conservation International Existing Work

Conservation International shared their existing work as a primer on coffee production and climate change. The majority of their completed work related to mapping suitable coffee growing area from 2010 into 2050. This also included the forested and protected land of producing nations. Below is an overview for each grouping of files:

a. Demand Models

Conservation International forecasted demand with both high and low consumptive models. Supply will ultimately settle to where demand sits, with prices fluctuating and farmers moving in and out of the market until supply meets demand. There are two significant inputs for this model. The first is the projected population for each country and the second is historical consumption per capita and future growth expectations. Combining these inputs gives the expected global demand for coffee into 2050. Some countries will see increased consumption while others are already near their peak. The noticeable differences between the high and low model are in the countries with historically low per capita consumption. The low model assumes that these countries will continue at a consumptive similar rate, while the high model assumes that the popularity and demand for coffee will grow significantly.

b. Forested and/or Protected Land

Conservation International used GIS tools to map and quantify the area of forested (not protected), protected (not forested), and forested and protected land. This data was used to

---

[59] *How Humidity Affects the Growth of Plants*. (n.d.). Retrieved March 11, 2021, from https://www.polygongroup.com/en-US/blog/how-humidity-affects-the-growth-of-plants/

[60] Kath, Jarrod & Mittahalli Byrareddy, Vivekananda & Mushtaq, Shahbaz & Craparo, Alessandro & Porcel, Mario. (2021). Temperature and rainfall impacts on robusta coffee bean characteristics. Climate Risk Management. 32. 100281. 10.1016/j.crm.2021.100281.

[61] *The effect of moisture and humidity on stored Coffee*. (n.d.). Retrieved April 21, 2021, from https://www.coffeerevolution.net/humidity-on-coffee/

[62] *Coffee Environment: Climate Conditions for Growing Coffee Beans*. (n.d.). Retrieved March 11, 2021, from http://www.coffeeresearch.org/agriculture/environment.htm

[63] Daggett, Z. (2015, June 28). How Does Altitude Affect Coffee and Its Taste in the Cup? *Perfect Daily Grind*. https://perfectdailygrind.com/2015/06/how-does-altitude-affect-coffee-and-its-taste-in-the-cup/

understand how much suitable area did not fall into one of these categories. Conservation International is driven to prevent deforestation and by using information related to demand, suitable land, and production impacts, CI can create an indicator of the pressure that will be felt to convert forested and/or protected areas into cropland.

c. Production Models

Conservation International calculated expected production needed to meet expected demand in five scenarios. Four of the five scenarios fall under a business-as-usual (BAU) category with coffee producing countries contributing a similar amount of product into 2050. Each BAU scenario has a different take on demand and potential yield – high consumption, high yield (HCHY), high consumption, low yield (HCLY), low consumption, high yield (LCHY), and low consumption, low yield (LCLY). A LCHY scenario would have the smallest environmental footprint while a HCLY would have the largest. The last scenario is a diversified sourcing scenario (DSS) which reallocates market share to smaller producing countries in an effort to diversify production risk. These production models take into account expected demand and expected yield to understand how much land will be needed for Arabica and Robusta production. The BAU models also hold the country allocation of Arabica and Robusta production constant.

VI. Methods

Our objective is to devise a methodology to project coffee supply into 2050 and to use Brazil and Vietnam as proxies of Arabica and Robusta production. This analysis considers the main contributors for coffee production, yield, and output. Bioclimatic and socio-economic parameters were incorporated in the analysis, though only quantifiable parameters were included in the projections. To supplement this model, the impact, direction, and magnitude of additional variables were described. This serves as an estimate of potential future conditions, as forecasting is limited by the availability of data and studies on observed impacts of these factors.

a. Geographical Focus

For the purpose of this report, we have focused on Brazil and Vietnam as they are the leading producers of Arabica and Robusta, respectively. Globally, Brazil is the largest producer of Arabica, yielding 38% of the entire Arabica market. Vietnam is the larger producer of Robusta in the world, producing 40% of the global Robusta market.

b. Modelling Production

We constructed a model to project supply into the future by applying bioclimatic conditions that result from expected climate scenarios, and their subsequent impacts on production. The model attempts to quantify and forecast anticipated temperature, pest, and land implications but does have limitations and makes input assumptions. These constraints are discussed in detail later in this report.

Figure 3 outlines the model. We start with an upper boundary of potential production and take into account all production impacts to create the projected supply. From there, the BAU demand is subtracted to calculate potential supply gaps and surpluses. Finally, because Conservation International has a focus on limiting deforestation, we calculated potential encroachment on forested/protected land to meet BAU demand.

Upper Most Boundary +/- Parameter Production Impacts *= Projected Supply*
- Project BAU Demand *= Supply Gaps or Surplus*
- Forested/Protected Area Impacted *= Forested/Protected Encroachment*

Figure 3. Constructed model to calculate: projected supply, supply gaps/surpluses, and potential forested/protected land encroachment

c. Calculating the Upper Limit of Production

CI created country specific geographic maps of the area suitable for Arabica and Robusta cultivation, regardless of whether only one cultivar was currently present. We utilized CI's calculations of suitable land to create a boundary of the upper limit of national coffee production. As identified land can only maximally produce within its capacity. Thus, if all of this suitable land is available for coffee crops, it acts as the upper most constraint. Knowing the limit of coffee production allowed parameter impacts to be taken into account.

Utilizing CI's suitable land data, we multiplied the high and low yield potentials by the suitable land area to calculate the best- and worst- case scenarios of the upper limit of production for selected countries. We used the allocation breakdown between Arabica and Robusta for each country to divide land that was deemed suitable for both varieties and assumed that that this breakdown will remain constant until 2050. For example, if a country produced 70% of Arabica and 30% Robusta, land deemed suitable for both cultivars would be divided up 70/30% as well.

d. BAU Demand

The BAU demand was calculated using the demand models CI had created. To allocate the demand to each country, their current Arabica/Robusta breakdown and current contribution to global production were incorporated and held constant through 2050.

e. Temperature Methodology

Temperature was one of the selected parameters which had quantifiable impacts on coffee production. We utilized a World Bank database of monthly historical temperature from 1901 to 2016 for each country[64]. This data was used to create a linear regression model that could forecast temperature into 2050. This simple model has two main components: a time series variable that serves as a measure of climate change through time and a monthly adjustment to account for the time of year. Overall, the trend showed rising temperatures into 2050.

i. Modelling Yield Impact

We used a recent publication to calculate the impact these rising temperatures have on coffee production. The authors found that for Robusta, every 1-degree Celsius increase over its ideal maximum temperature of 24.1-degrees Celsius decreased crop yield by 14%[65]. This research was extrapolated to make an informed judgement about the effect of temperature on

[64] *World Bank Climate Change Knowledge Portal*. (n.d.). Retrieved March 23, 2021, from https://climateknowledgeportal.worldbank.org/

[65] Kath, J., Byrareddy, V. M., Craparo, A., Nguyen-Huy, T., Mushtaq, S., Cao, L., & Bossolasco, L. (2020). Not so robust: Robusta coffee production is highly sensitive to temperature. *Global Change Biology*, *26*(6), 3677–3688. https://doi.org/10.1111/gcb.15097

Arabica, as no publications outlined this effect. As Robusta is more heat tolerate and less sensitive to changes in temperature than Arabica, the 14% yield impact can act as a lower boundary prediction for Arabica. It is unlikely that Arabica will have a smaller yield impact than 14% given what is known about its heat tolerance[66].

ii. Projecting Impact

We combined the projected temperature and modelled yield impacts to calculate production impact based on the changing temperature. We used a baseline of 24 degrees Celsius as the ideal maximum temperature for Arabica. The range of Arabica temperature 16-24 degrees Celsius and without objective research identifying the ideal maximum, we used the upper boundary as the baseline[67]. We used a baseline of 24.1 degrees Celsius as the ideal maximum temperature for Robusta as suggested in the research to signify the upper boundary of normal production[68]. The predicted temperature was subtracted from the ideal maximum temperature, with the difference then multiplied by the expected yield impact. For predicted temperatures that do not exceed the maximum ideal temperature, the yield impact is calculated as zero. The average of this impact is taken over each time period to calculate the expected production effect.

f. Pest and Fungus Methodology

We were able to model the impact of some pests, funguses, and diseases to an extent, although our methods for the latter are specialized to the country due to data acquisition limitations. Unlike temperature where there was enough research and data to conform an algorithm, we had to rely on historical observations to create best- and worst- case scenarios. For example, there was an epidemic of coffee leaf rust that decimated coffee production in Central and South America in the early 2010s. We also know that coffee leaf rust is a run-of-the-mill issue that farmers deal with every year. We assumed the worst-case scenario here to be similar to the one in the early 2010s. We constructed the best-case scenario as the standard yearly impact on production. The best- and worst – case scenario impacts were applied uniformly to each decade due to a lack of adequate information regarding event frequency. The appendix includes the methodology for the coffee berry borer in Colombia and Ethiopia, for which we were able to create an algorithm to calculate production impact from available information specific to these countries. Seasonality of pest presence and influence was not incorporated into model. *Colletotrichum gloeosporioides* causes anthracnose disease on coffee berries. We assumed a 15% worst-case scenario and 0% best-case scenario yield impact to Robusta production, extrapolating from documented impacts of *C. gloeosporioides* on Arabica production in Vietnam[69].

g. Limits to Quantitative Methodology

Most parameters that affect production lacked clear documentation of their influence on yield. To supplement the limited quantitative analysis, we constructed a qualitative analysis describing the magnitude and direction of each variable to provide concrete insight into how that

---

[66] Dzombak, R. (2020). *Coffee's robust back-up bean isn't as resistant to climate change as once thought*. Massive Science. Retrieved March 11, 2021, from https://massivesci.com/articles/coffee-climate-change-robusta-arabica-temperature-hot-cold/

[67] *Coffee Environment: Climate Conditions for Growing Coffee Beans*. (n.d.). Retrieved March 11, 2021, from http://www.coffeeresearch.org/agriculture/environment.htm

[68] Dzombak, R. (2020). *Coffee's robust back-up bean isn't as resistant to climate change as once thought*. Massive Science. Retrieved March 11, 2021, from https://massivesci.com/articles/coffee-climate-change-robusta-arabica-temperature-hot-cold/

[69] Nguyen, T.H.P., Säll, T., Bryngelsson, T. and Liljeroth, E. (2009), Variation among *Colletotrichum gloeosporioides* isolates from infected coffee berries at different locations in Vietnam. Plant Pathology, 58: 898-909. https://doi.org/10.1111/j.1365-3059.2009.02085.x

parameter individually affects production. Many parameters will have the same directional impact for all countries while the size of magnitude will vary. Some parameters were country specific, while others impacted coffee globally. See Figure 1 in the appendix for a comparison of all identified parameters that affect coffee production for the top 80% production countries.

VII. Results

This section is comprised of the results for Brazil and Vietnam from our quantitative and qualitative analyses.

a. Quantitative Metrics

i. Land

Brazil: Brazil can expect its potential suitable land for Arabica to decrease by 65% between 2010 and 2050. Yield predictions in the future vary depending on advances in technology, but they should remain stable until 2050, with the potential to increase by 12%. As of 2010, 27% of the land suitable for either cultivar was forested and/or protected. This percentage is relatively stable until 2050 because the proportion of forested, protected, and coffee-suitable land decrease by the same amount. Figure 5 considers forested and/or protected land in Brazil at a baseline – assuming no parameter impacts. The percent flexibility of total production number is useful in understanding how much area Brazil has to deal with negative impacts before they are pushed to forested/protected land. Fortunately, Brazil does have a fair amount of suitable land available that is neither forested or protected.

	Forecast for Brazil's Arabica Production 2020-2050 (in millions)					
	2020-2030		*2031-2040*		*2041-2050*	
	Worst	Best	Worst	Best	Worst	Best
Total Potential Suitable Production (kg)	91,331.1	91,331.1	75,223.3	77,103.9	52,028.1	58,367.3
BAU Demand	2,524.4	2,257.5	3,464.9	2,488.1	4,720.7	2,682.2
Supply Gap/Excess	88,806.7	89,073.6	71,758.4	74,615.8	47,307.5	55,685.2
Forested (not protected)	14,158.6	14,158.6	12,394.0	12,703.9	9,457.5	10,609.8
Protected (not forested)	1,363.2	1,363.2	1,171.7	1,201.0	869.5	975.4
Forested and Protected	959.5	959.5	890.9	913.2	737.8	827.7
Land (ha) Available (Encroached)	46.9	47.0	35.4	36.1	23.6	25.1
% Flexibility	79%	79%	76%	78%	70%	74%

Figure 5. Baseline potential forested/protected land encroachment without factoring in any parameter impacts for Brazil's Arabica

Vietnam: Vietnam can expect its potential suitable land for Robusta to decrease by and 45% respectively between 2010 and 2050. Yield predictions in the future depend on advance in technology but they should remain stable until 2050 with the potential to improve by 12%. In 2010, 56% of land suitable for either cultivar was forested and/or protected. This percentage will increase to 68% by 2050. Figure 6 considers forested and/or protected land in Vietnam at a baseline – assuming no parameter impacts. The percent flexibility of total production line provides an idea of how much area Vietnam may have to deal with negative impacts of productivity declines before farmers will feel pressure to expand into forested and/or protected land. Vietnam does not have as room to play with and each decade, they will see this flexibility decrease. Many parameters we have studied easily have impacts that would consume any non-forested/protect available and Vietnam will soon be stressed to expand the coffee production area into forested and/or protected land.

Forecast for Vietnam's Robusta Production 2020-2050 (in millions)	2020-2030		2031-2040		2041-2050	
	Worst	Best	Worst	Best	Worst	Best
Total Potential Suitable Production (kg)	20,385.2	20,385.2	18,476.9	18,938.8	14,818.0	16,623.4
BAU Demand	2,022.3	1,808.5	2,775.7	1,993.2	3,781.7	2,148.7
Supply Gap/Excess	18,362.9	18,576.7	15,701.2	16,945.6	11,036.3	14,474.8
Forested (not protected)	10,279.9	10,279.9	9,801.0	10,046.0	8,390.9	9,413.3
Protected (not forested)	319.5	319.5	261.3	267.8	178.5	200.3
Forested and Protected	1,203.9	1,203.9	1,177.4	1,206.8	1,038.9	1,165.5
Infringement	6,559.6	6,773.5	4,461.5	5,424.9	1,428.0	3,695.7
Land (ha) Available (Encroachment)	2.3	2.3	1.5	1.7	0.5	1.1
% Flexibility	36%	36%	28%	32%	13%	26%

Figure 6. Baseline potential forested/protected land encroachment without factoring in any parameter impacts for Vietnam's Robusta

ii. Temperature

Brazil: Temperature increases are expected to impact Brazil's production. Arabica production could drop by 21% (2020-2030), 22% (2031-2040), and 23% (2041-2050). The likelihood of the losses increases from 83% to 100% by the decade 2041-2050 for Arabica production. Figure 7 is a sensitivity analysis of the expected production impact from temperature increases on Brazil's Arabica production. As mentioned in the temperature methodology, the 14% yield impact came from a Robusta study and we adapted it to Arabica knowing that this would be a lower bound as this cultivar is more sensitive to temperature changes

Sensitivity Analysis of Yield Impact on Brazil's Arabica by Decade

	Expected Production Impact		
Yield Impact	2020-30	2031-40	2041-50
14%	21%	22%	23%
15%	23%	24%	25%
16%	24%	25%	27%
17%	26%	27%	28%
18%	27%	29%	30%

Figure 7. Sensitivity analysis of yield impact due to temperature increases on Arabica production

Vietnam: The impact of temperature on Robusta production in Vietnam is negative. Increasing temperatures could impact production by 21% in the decades 2020-2030, by 22% in and 2031-2040 and by 22% from 2041-2050. The likelihood of this happening is 58% in the first two decades and 59% in the final decade. Figure 8 is a sensitivity analysis of the expected production impact from temperature increases on Vietnam's Robusta production.

Sensitivity Analysis of Yield Impact on Vietnam's Robusta by Decade

	Expected Production Impact		
Yield Impact	2020-30	2031-40	2041-50
12%	18%	18%	19%
13%	19%	20%	20%
14%	21%	21%	22%
15%	22%	23%	23%
16%	24%	24%	25%

Figure 8. Sensitivity analysis of yield impact due to temperature increases on Robusta production

iii. Pest and Fungus

Brazil: The impact of pests and fungi disease in Brazil is negative. In the worst scenario, Brazil is expected to lose 65% of the yield production, and is expected to lose 50% of yield production due to fungi diseases. Even while in the best scenario, the ratios are as high as 20% and 30% because of pests and fungi, accordingly.

Pest and Fungi Impact on Brazil's Arabica Production		
Pest/Fungus	Worst-Case	Best-Case
Coffee Berry Borer	30%	5%
Leaf Miner*	35%	15%
Coffee Leaf Rust	50%	30%

*Evidence of technology decrease Leaf Miner by 50%

Figure 9. Consolidated results of pest and fungi production impact for Brazil

Vietnam: The impact of pests is relatively moderate in Vietnan compared with that of Brazil. In the worst scenario, Vietnam is expected to lose 15% of total production because of pests, and in the best scenario, Vietnam will not lose any yield production for this reason.

b. Qualitative inputs

To supplement our model, we performed a qualitative analysis on the socioeconomic and some bioclimatic parameters for which yield impacts were not able to be quantified. We report the direction and magnitude of these parameters to understand how these impacts on production may change in the future. More descriptions can be found in the Appendix.

a. Urbanization negatively impacts production
b. Contracts and cooperative pricing mechanisms provide access to markets and price floors and incentivize farmer retention, thus positively impacting production
c. Certifications positively impact production through the above mechanisms
d. Competing Crops, Land Uses, & Encroachment negatively impact production
e. Extreme Weather negatively impact production
f. National Policies positively impact production

VIII. Discussion

Our model and thus its findings are limited to the quantifiable parameters and for the purpose of this report, to Brazil's Arabica production and Vietnam's Robusta production. Available literature varied by desired cultivar, country, and parameter. It was also difficult to generate broad projections of these parameters' impacts, as they are very condition-specific and are anticipated to change when coupled with changing climate patterns during different production stages. These factors prevent our analysis from being as comprehensive or descriptive as originally desired. With the publication of additional impact yields, the model can be increasingly built out to more accurately forecast coffee supply into 2050.

a. Quantified Parameters

i. Forecasted Temperature

Our model projected temperature changes into 2050 by utilizing World Bank historic temperature data. The temperature provided by the World Bank is an average across each country and not specific to the regions where coffee is grown. We calculated the likelihood of these yield decreases occurring, as the percentage of the frequency of temperature exceeding the ideal maximum temperature. This was ultimately not included in our projections, as our client desired best- and worst- case scenarios. If there was a potential for a scenario to occur, it was utilized in the worst-case scenario category.

Though potentially not as tolerant to very high temperatures as previously thought, Robusta has greater adaptability and productivity to suboptimal conditions. As rising CO_2 levels change coffee's response to temperature and water[70], this should be considered in future analysis. Additionally, our model was structured to identify potential yield loses due to conditions outside of an ideal range, rather than attempting to optimize yield, as it is unfeasible to control climate conditions in the field. Finally, utilizing our projected temperature values may skew output information as the IPCC's Representative Concentration Pathways (RCPs) and ERA5 predict future temperature that could significantly deviate from historic patterns, depending on the model (RCP8.5, RCP6, RCP4.5, RCP2.6)[71].

ii. Pest, Fungus, and Disease

We were unable to quantify the impact of pest presence on coffee production for many pests and areas. For example, we could not obtain specific impacts of the numerous parasitic root nematodes that affect Arabica and Robusta production in Vietnam and Brazil[72]. Although historic events do not necessarily predict future events, they do provide an idea of scale and vulnerable entities. Thus, while we extrapolated this impact, we were not able to discern the distribution nor the frequency of worst-case scenario events. Future iterations of this model may incorporate timing of pest presence on crop growth, as damage from external organisms have varied results depending on occurrence during, for example, flowering versus fruiting stages, with effects represented differently during a tree's lifetime as well[73]. Lastly, temperature, precipitation, and humidity play a large role on the abundance and proliferation of pest, funguses, and diseases and were not captured in our model.

iii. Forested and Protected Areas

Conservation International's GIS team identified current forested and protected areas that fall within areas that are suitable to grow coffee. This was used to delineate how much forested and protected land might be infringed upon if production from currently planted land is not adequate to meet demand. Given expected yield and demand, CI calculated a rough estimate of how much of the forested and protected land would be at risk for being converted into cultivated land. For our analysis, suitable land was not differentiated to specific cultivars [74]. As Arabica yields a higher price and is often preferred by consumers, it may be beneficial to specify this difference in future work, to maintain or disincentivize expanding Arabica growing areas. Furthermore, this work assumed coffee would be the target crop for land conducive to coffee

---

[70]Kath, J, Byrareddy, VM, Craparo, A, et al. Not so robust: Robusta coffee production is highly sensitive to temperature. *Glob Change Biol*. 2020; 26: 3677– 3688. https://doi.org/10.1111/gcb.15097

[71] Wayne, G. P. (2013, August 30). *Now available: A guide to the IPCC's new RCP emissions pathways | Graham Wayne*. The Guardian. http://www.theguardian.com/environment/climate-consensus-97-per-cent/2013/aug/30/climate-change-rcp-handy-summary

[72] Trinh, Phap & De, Eduardo & de la Peña, Eduardo & Nguyen, Chau & Nguyen, Hoa & Moens, Maurice. (2009). Plant-parasitic nematodes associated with coffee in Vietnam. Russian Journal of Nematology. 17. 73-82.

[73] Nguyen, T.H.P., Säll, T., Bryngelsson, T. and Liljeroth, E. (2009), Variation among *Colletotrichum gloeosporioides* isolates from infected coffee berries at different locations in Vietnam. Plant Pathology, 58: 898-909. https://doi.org/10.1111/j.1365-3059.2009.02085.x

[74] *Coffee Environment: Climate Conditions for Growing Coffee Beans*. (n.d.). Retrieved March 11, 2021, from http://www.coffeeresearch.org/agriculture/environment.htm

cultivation, rather than the competing crops or land uses that may be more profitable to invest in. During discussions with subject matter experts, we learned that in some countries, development encroaches on crop land is not documented. The opportunity cost component has been under appreciated in this analysis, as agriculture under changing conditions becomes increasingly resource intensive.

It is unknown whether suitable land considers areas that are currently planted, even if they fall beyond the programed conditions. Thus, it is uncertain whether currently cultivated land that is not categorized presently as suitable land, will continue to be able to produce coffee in the future. This work will influence supply calculations, as well as aid in supporting farmers to identify adapting production or transitioning to other crops or livelihoods. Finally, as suitable land loses may be made up elsewhere, it is unknown whether the local communities and infrastructure will be amenable to beginning coffee cultivation.

b. Non-Quantified Parameters

i. National Policies

For many of the primary coffee producing countries, over 50% of their total export value comes from coffee exports, making them heavily reliant on the industry[75]. National-level economic and policy instruments can positively impact coffee production through many avenues. This can be accomplished through increased access to specialty coffee markets and supporting coffee exports through regulations such as taxation, export provision and national quality standards[76,77,78]. Additional policies can support smallholder farmers with respect to adverse price fluctuations. When market prices are at or below production costs, the Brazilian government intervenes with policies to compensate the shortfall[79]. Lastly, nations can provide education and technical resources that invest in farming communities and increase yield. The Vietnam Ministry of Agriculture and Rural Development partnered with the World Bank to increase productivity on existing farms by replacing old coffee trees with younger trees to improve yield by up to 80%[80]. These economic and policy approaches can be utilized globally and can incentivize, or if structured to support other industries disincentivize, coffee production, though implementation and policy specifications must be designed regionally (see Appendix).

ii. Pricing and Cost Structures

Using the economic model of supply and demand, a commodity's price is determined by how much of it is produced in relation to its demand by consumers. Entry and exit in the coffee market occur as prices fluctuate, and the opportunity cost of remaining in a specific agricultural industry depends on labor supply, wages, resource intensiveness, and farm-gate price[81]. When

---

[75] Reyes, H., & Jose, J. (2014). The Role of Futures Prices in Pricing Commodity Exports of Developing Countries. *LSU Master's Theses*, 1585. Retrieved from: https://digitalcommons.lsu.edu/gradschool_theses/1585

[76] Behuria, P. (2020). The domestic political economy of upgrading in global value chains: how politics shapes pathways for upgrading in Rwanda's coffee sector. *Review of International Political Economy*, 27(2): 348-376. Retrieved from: https://www-tandfonline-com.proxy.lib.duke.edu/doi/full/10.1080/09692290.2019.1625803

[77] Andoko, E., Zmudczynska, E., & Liu, W. (2020 June 1). A Strategy Review of the Coffee Policies and Development by the Indonesian Government. FFTC Agricultural Policy Platform. Retrieved from: https://ap.fftc.org.tw/article/1874

[78] Andoko, E., Zmudczynska, E., & Liu, W. (2020 June 1). A Strategy Review of the Coffee Policies and Development by the Indonesian Government. FFTC Agricultural Policy Platform. Retrieved from: https://ap.fftc.org.tw/article/1874

[79] Food and Agriculture Organization of the United Nations (FAO). (2012). *Policy responses to high food prices in Latin America and the Caribbean.* Trade and Market Division, FAO. Rome, Italy. Retrieved from: http://www.fao.org/3/i3909e/i3909e.pdf

[80] Hoang, H., Tran, L.H., Nguyen, T.H. *et al.* Occurrence of endophytic bacteria in Vietnamese Robusta coffee roots and their effects on plant parasitic nematodes. *Symbiosis* **80,** 75–84 (2020). https://doi.org/10.1007/s13199-019-00649-9

[81] Luna, Fatima & Wilson, Paul. (2015). An Economic Exploration of Smallholder Value Chains: Coffee Transactions in Chiapas, Mexico. International Food and Agribusiness Management Association. 18.

the price of a good increases, there is more entry into the system, and because for our use, coffee is a crop, it may take years for an eventual oversupply of the commodity to occur. If there is an oversupply of the product, price drops and the revenue earned by coffee producers subsequently falls. This results in producers selling their products at a price which does not compensate[82] [83] [84] [85] [86]. These conditions make it difficult for farmers to stay in the industry or grow their production to enjoy economies of scale. [87].

iii. Certifications, Cooperatives, and Supply Chain Integration

The growing global demand for niche products, such as verified sustainable and equitable coffee, has had a measurable impact on livelihoods and land-use change around the world. Although certifications which aim for social and environmental improvements could be a step in the right direction for the coffee industry, collected data and studies have shown mixed results. Today, the major coffee certifications include Fairtrade, UTZ Kapeh, Organic, Rainforest Alliance, and Common Code[88]. These and other sustainability-oriented coffee certification frameworks outline a mix of similar qualification criteria that cover social welfare, environmental stewardship, and economic viability[89]. In 2018, 745,550 million tons of coffee were produced by fair trade organizations, and 207,600 million tons coffee were sold as fair trade[90]. Despite this prevalence, research has provided different and even opposing results of the impact certification schemes has made on coffee production. Early studies conclude that fair trade strengthens producer organizations, reinforces farmers' well-being, and improves coffee production practices[91]. Later studies argue that fair trade's strict certification requirements may cause uneven economic advantages for coffee growers and lower coffee quality for consumers, which ultimately prevent a sustainable coffee supply chain (see Appendix)[92].

Fridell et al. (2014) emphasizes the need to first build and support profitable coffee production, and then add sustainable practices on top[93]. Farmers who find themselves with higher input costs without the higher revenue find themselves failing to thrive. They found that farmers could maintain the same level of income while reducing their environmental burden by more than 50% - there is no tradeoff between farm income and environmental degradation and

---

[82] International Coffee Council (ICO). (2014 Mar 3-7). World coffee trade (1963 – 2013): A review of the markets, challenges and opportunities facing the sector. International Coffee Council 112th Session, London, UK. http://www.ico.org/news/icc-111-5-r1e-world-coffee-outlook.pdf

[83] The Global Warming Policy Forum (GWPF). (2019, Oct 10). *New World Record: Oversupply of Coffee Beans Sends Global Prices Tumbling*. Retrieved from: https://www.thegwpf.com/new-world-record-oversupply-of-coffee-beans-sends-global-prices-tumbling/

[84] Luna, Fatima & Wilson, Paul. (2015). An Economic Exploration of Smallholder Value Chains: Coffee Transactions in Chiapas, Mexico. International Food and Agribusiness Management Association. 18.

[85] Luna, Fatima & Wilson, Paul. (2015). An Economic Exploration of Smallholder Value Chains: Coffee Transactions in Chiapas, Mexico. International Food and Agribusiness Management Association. 18.

[86] Perfect Daily Grind. (2016 June 22). *What Effect Does The C Market Have on Small Coffee Farmers?*. Retrieved from: https://perfectdailygrind.com/2016/06/what-effect-does-the-c-market-have-on-small-coffee-farmers/

[87] Luna, Fatima & Wilson, Paul. (2015). An Economic Exploration of Smallholder Value Chains: Coffee Transactions in Chiapas, Mexico. International Food and Agribusiness Management Association. 18.

[88] Nguyen, T. M. C., Chien, L., & Chen, S. (2015). Impact of Certification System on Smallhold Coffee Farms' Income Distribution in Vietnam. Asian Journal of Agriculture & Rural Development. **5** (6) : 137 – 149.

[89] May, P. H., Mascarenhas, G. C. C., & Potts, J. (2004). Sustainable Coffee Trade: The Role of Coffee Contracts. International Institute for Sustainable Development.

[90] Fairtrade Labelling Organizations International (FLO). (2018 Sep 12). Key Data: Fairtrade Coffee. Retrieved from: https://www.fairtrade.net/impact/key-data-fairtrade-coffee

[91] Bacon, C.M., Méndez, V.E., Flores Gómez, M.E., Stuart, D., & Díaz Flores, S.R. (2008). Are Sustainable Coffee Certifications Enough to Secure Farmer Livelihoods? *The Millenium Development Goals and Nicaragua's Fair Trade Cooperatives,*5(2): 259 – 274. https://doi.org/10.1080/14747730802057688

[92] Haight, C. (2011). The Problem With Fair Trade Coffee, Stanford Social Innovation Review. Retrieved from: https://ssir.org/articles/entry/the_problem_with_fair_trade_coffee#

[93] Fridell, G. (2014). Fair Trade Slippages & Vietnam Gaps: The Ideological Fantasies of Fair Trade Coffee. Third World Quarterly. 35 (7) : 1179 – 1194.

only adds to the eco-efficiency and is further explored in our management section [94]. Despite their shortcomings, certifications bring awareness and signal better practices for consumers who are thousands of miles from the product origin. Some certification schemes provide farmers access to larger markets due to projects that aid with financial and technical assistance that allow them to improve coffee yield and increase exports of fair trade or similarly certified grains[95]. Additional benefits can be increased bargaining power[96] and incentivization of responsible natural resource use and restoration of ecosystems[97].

Alternative contracting systems like the Starbucks Preferred Supplier Program and vertical supply chain integration have substantial benefits for their respective corporations[98]. Companies can choose to integrate multiple stages of the value chain or specialize in only one step and vertically integrating the entire supply chain allows a company to be involved with its product from start to finish, working directly with the growers and simultaneously engaging with consumers. This has two advantages: first, the company can ensure a steady supply of coffee with non-compete agreements, and second, the company ensures farmers follow sustainable practices that allow them to charge a premium[99]. This approach also benefits smallholder producers by increasing their profit margins[100]. In contrast, Dunkin Donuts outsources all of their supply chain needs, as it depends on where the company sees their competitive advantage[101]. Smaller companies more often specialize in one aspect of the value chain, though this is not always the case. Counter Culture Coffee in Durham, NC touts its sustainability practices, including transparency and involvement along the entire value chain[102].

iv. Competing Crops, Land Uses, and Land Encroachment

The global coffee supply is determined, in part, by the area under production. Competition for land and the factors influencing land-use change determine, in part, whether the area under production will increase or decrease. To grow the coffee, farmers and landowners must be incentivized to either continue cultivating coffee or choose coffee over other crop types and land. As farm gate prices rise and fall over time, governments and private landowners are motivated to change the land use type between natural forest, perennial or annual crops, and other options[103]. When coffee prices are high, there is an increased incentive to convert forested land into cultivated fields. Countries producing agricultural commodities at scale struggle to

---

[94] Ho, T. Q., Hoang, V., Wilson, C., & Nguyen, T. (2018). Eco-Efficiency Analysis of Sustainability-Certified Coffee Production in Vietnam. Journal of Cleaner Production. 183: 251 – 260.
[95] World Bank. (2013). Support to coffee farmers awakens development in rural Sao Paulo, Brazil. Retrieved from: https://www.worldbank.org/en/news/feature/2013/09/25/Brazil-fair-trade-coffee-farming
[96] Giuliani, E., Ciravegna, L., Vezzulli, A., Kilian, B. (2017). Decoupling Standards from Practice: The Impact of In-House Certifications on Coffee Farms' Environmental and Social Conduct. World Development, 96: 294-314. Retrieved from: https://doi.org/10.1016/j.worlddev.2017.03.013
[97] Pinto, L.F.G., Gardner, McDermott, C.L., & Ayub, K.O.L. (2014). Group certification supports an increase in the diversity of sustainable agriculture network–rainforest alliance certified coffee producers in Brazil. *Ecological Economics*, 107: 59-64. Retrieved from: https://doi.org/10.1016/j.ecolecon.2014.08.006
[98] May, P. H., Mascarenhas, G. C. C., & Potts, J. (2004). Sustainable Coffee Trade: The Role of Coffee Contracts. International Institute for Sustainable Development.
[99] Guest Contributor. (2017, May 10). Supply Chain Putting the Star in Starbucks. *Fronetics*. https://www.fronetics.com/supply-chain-putting-star-starbucks/
[100] Luna, Fatima & Wilson, Paul. (2015). An Economic Exploration of Smallholder Value Chains: Coffee Transactions in Chiapas, Mexico. International Food and Agribusiness Management Association. 18.
[101] Guest Contributor. (2017, May 10). Supply Chain Putting the Star in Starbucks. *Fronetics*. https://www.fronetics.com/supply-chain-putting-star-starbucks/
[102] *Coffee Sustainability | Sustainability of Coffee*. (n.d.). Counter Culture Coffee. Retrieved March 23, 2021, from https://counterculturecoffee.com/sustainability
[103] Ambinakudige, S. & Choi, J. (2009). Global Coffee Market Influence On Land-Use & Land-Cover Change in the Western Ghats of India. Land Degrad. Develop. 20: 327 – 335.

balance improving farmer livelihood and maintaining their global competitiveness with environmental degradation. The risk of deforestation may increase due to the projected growth in demand for coffee. Conserving natural forests, however, is important due to the myriad ecosystem services they provide, such as habitat, carbon sequestration, air and water filtration, and erosion control[104] [105].

Land-use type depends on the owner's discount rate, which is lower for corporations and higher for families. Retention of currently cultivated areas is determined by whether a region can produce demanded products and the profitability of alternative crops and the land use type of adjacent properties. Land encroachments from adjacent land uses offer occur when these operations yield higher profit margins. Such encroachment is also discouraged by the popularization of shade grown coffee, which diversifies revenue streams[106]. The combination of opportunity cost of producing coffee and the suitability of land may change where coffee is grown in the future (see Appendix).

Changing climate conditions will change how conducive an area is to growing coffee or other crops, or supporting other activities. Ainhoa Magrach has published descriptive work on the intricacies of geographic shifts due to changing climate and pest conditions[107]. From the quantitative results mentioned above, we can see Arabica is predicted to undergo more loss of suitable land than Robusta. This finding aligns with the trend of the land use conversion from Arabica to Robusta production and the belief that Robusta may at least partially replace lost Arabica supply, as it is less susceptible to damage from high temperatures[108]. Robusta, however, is also vulnerable to increasing temperatures, could suffer global losses as well, making it less able to supplement this potential gap as originally presumed[109]. If economically feasible, some coffee production can potentially shift to higher altitudes, which favor Arabica production, or latitudes, for Robusta production[110].

v. Extreme Weather Events

A warming climate will increase the frequency and intensity of extreme weather events. Heat waves will be hotter and droughts will last longer, along with devastating impacts of changing precipitation patterns. Storms will have stronger winds and more rain, with increasing flood frequency and severity[111]. All of these events will hamper coffee production and make it difficult for farmers to return to production[112].

---

[104] Ricketts, T. H., Daily, G. C., Ehrlich, P. R., & Michener, C. D. (2004). Economic Value of Tropic Forest to Coffee Production. PNAS. 101 (34) 12579 – 12582.

[105] Priess, J. A., Mimler, M., Klein, A. M., Schwarze, S., Tscharntke, T., & Steffan-Dewenter, I. (2007). Linking Deforestation Scenarios to Pollination Services & Economic Returns in Coffee Agroforestry Systems. Ecological Applications. 17 (2) 407 – 417.

[106] Batista, F. (2019, June 8). As Coffee Gets Cheaper, Brazil Finds Ways to Grow More for Less. *Bloomberg.Com*. https://www.bloomberg.com/news/features/2019-06-08/as-coffee-gets-cheaper-brazil-finds-ways-to-grow-more-for-less

[107] Magrach, A., & Ghazoul, J. (2015). Climate and Pest-Driven Geographic Shifts in Global Coffee Production: Implications for Forest Cover, Biodiversity and Carbon Storage. PLOS ONE, 10(7), e0133071. https://doi.org/10.1371/journal.pone.0133071

[108] Bunn, C., Läderach, P., Ovalle Rivera, O. *et al.(2015).* A bitter cup: climate change profile of global production of Arabica and Robusta coffee. *Climatic Change* **129:** 89–101. Retrieved from: https://doi.org/10.1007/s10584-014-1306-x

[109] Kath, J, Byrareddy, VM, Craparo, A, et al. Not so robust: Robusta coffee production is highly sensitive to temperature. *Glob Change Biol*. 2020; 26: 3677– 3688. https://doi.org/10.1111/gcb.15097

[110] Bunn, C., Läderach, P., Ovalle Rivera, O. *et al.* (2015). A bitter cup: climate change profile of global production of Arabica and Robusta coffee. *Climatic Change* **129,** 89–101. Retrieved from: https://doi.org/10.1007/s10584-014-1306-x

[111] *Climate change and eastern Africa: A review of impact on major crops—Adhikari—2015—Food and Energy Security—Wiley Online Library*. (n.d.). Retrieved April 21, 2021, from https://onlinelibrary.wiley.com/doi/full/10.1002/fes3.61

[112] *Easing the impact of climate change on coffee growers*. (2020, September 4). Science. https://www.nationalgeographic.com/science/article/partner-content-impact-climate-change-on-coffee-growers

vi. Migration and Urbanization

Coffee farming is intensive works that ebbs and flows with the production cycle. Permanent workers are needed for crop maintenance throughout the year and additional temporary workers are required during the high work seasons. Each hectare of Arabica needs on average 400-man days each year and each Robusta hectare needs 300-man days, where 1-man day equals one person's work for one day[113]. Coffee is most often produced in rural environments and reliant on permanent and migrant workers in the area (see Appendix).

Migration affects coffee production as many temporary workers migrate either from other parts of the same country or from neighboring countries to complete the coffee berry harvests. When farmers don't have enough workers to harvest ripe berries, the berries will fall and farmers will not get full price or in the worst-case scenario, they will not be able to sell them at all. The other side of migration comes from farmers who can no longer make a living farming coffee and head to other countries in search of a better life. When coffee prices consistently undercut the farmers by being below their cost, farmers and their families turn to alternative livelihoods. Largely due to lower coffee prices or yields, changing climate conditions is posed to make this a more common occurrence. The World Bank expects that by 2050, roughly 143 million people in Sub-Saharan Africa, Latin America, and South Asia will be forced to move because of climate change impacts, as climate refugees[114].

Urbanization is another component of agricultural labor supply. We used urbanization as a proxy variable to estimate changes to the available workforce in rural areas where coffee is produced (Figure 9). Urbanization is the global phenomenon of citizens moving from rural to urban areas that occurs as technology advances and countries utilize competitive advantages to further develop their economies[115]. While the latter portion of the value chain is fulfilled by urban populations in the roasting, packaging, etc, and urbanization increases coffee consumption, the migration of rural populations away from farms substantially affects the opportunity cost of remaining in this industry[116].

Country	% Rural Population	% Rate Urbanization
Brazil	12.9%	1.05%
Colombia	18.6	1.22
Ethiopia	78.3	4.63
Honduras	41.6	2.75
India	65.1	2.37
Indonesia	43.4	2.27
Vietnam	62.7	2.98

Figure 9. Rural population and urbanization rate of top producing coffee nations, with % urbanization as annual rate of change from 2015-2020[117].

[113] *Social Inclusion of Migrant Coffee Plantation Workers in Kodagu District of Karnataka*. (2017). *5*(3), 4. https://www.ijedr.org/papers/IJEDR1703181.pdf
[114] *Groundswell: Preparing for Internal Climate Migration.* (n.d.). World Bank Group. Accessed: 11 March 2021. http://documents1.worldbank.org/curated/en/983921522304806221/pdf/124724-BRI-PUBLIC-NEWSERIES-Groundswell-note-PN3.pdf
[115] *Overview*. (n.d.). World Bank. Retrieved April 21, 2021, from https://www.worldbank.org/en/topic/urbandevelopment/overview
[116] Luna, Fatima & Wilson, Paul. (2015). An Economic Exploration of Smallholder Value Chains: Coffee Transactions in Chiapas, Mexico. International Food and Agribusiness Management Association. 18.
[117] *Urbanization—The World Factbook*. (n.d.). Retrieved March 23, 2021, from https://www.cia.gov/the-world-factbook/field/urbanization/

IX. Impact and Recommendations

a. Management Practice Impacts on Coffee Production

Projected production numbers can be improved through management practices. Efficient resource use can increase productivity to increase profit margins and optimize currently planted areas to increase yield on existing farms and disincentivize expansion into unharvested areas. The following sections offer an overview of the best practices that Conservation International can expand upon and support to counteract the adverse impacts of climate change, which may create supply gaps in the future.

i. Soil & Nutrient Management

Farmers of agricultural commodities have to balance profitability with the long-term negative effects that continuous, intensive monocropping can have on the environment. Soil health and nutrient management are topics that are often ignored in the search for higher yields. Every year, plantations suffer nutrient losses during the harvest of green coffee beans, tree growth, tree removal, erosion, and leaching[118] [119]. When farmers add nutrients back to the system, there is a misguided belief that over fertilization will increase yields. In reality, the constant use of fertilizers leads to undesirable changes in the soil, such as a shift in pH and an accumulation of nitrogen[120]. Additionally, a low to medium fertilizer rate can maintain relatively high yields, but dramatically increase a farmer's net income by decreasing input[93]. Nutrient management needs to focus as much on long-term soil health as it does short-term fertilizer usage.

Continuous cropping of perennial plants can also lead to a buildup of soil pathogens, the degradation of soil physical properties, accumulation of autotoxins, and a shift in the native soil microbe species[121]. One study attributes the long-term decrease in plantation productivity to a decrease in soil organic matter, soil acidification, salt stress, and an accumulation of inhibiting compounds. They also found that soil bacterial and fungal diversity decreased with increasing years in monoculture. The appendix outlines the authors' recommended steps for remediating overworked soil[122].

Robusta varieties store more soil organic carbon (SOC) than Arabica varieties, but Arabica performs better than Robusta when intercropped with fruit trees[123]. Where feasible, transition Arabica plantations into a mixed culture of coffee, fruit, and leguminous trees. A shaded, multi-species coffee system has the potential to create more belowground biomass, store more SOC, and improve nutrient availability more than a full-sun, monocropped system[124].

---

[118] Byrareddy, V., Kouadio, L., Mushtaq, S., & Stone, R. (2019). Sustainable Production of Robusta Coffee Under a Changing Climate: A 10-Year Monitoring of Fertilizer Management in Coffee Farms in Vietnam & Indonesia. Agronomy. **9** 499.

[119] Pham, T., Nguyen, N. H., Yen, P. N. D., Lam, T. D., & Le, N. T. T. (2020). Proposed Techniques to Supplement the Loss in Nutrient Cycling for Replanted Coffee Plantations in Vietnam. Agronomy. **10** 905.

[120] Capa, D., Pérez-Esteban, J., & Masaguer, A. (2015). Unsustainability of Recommended Fertilization Rates for Coffee Monoculture Due to High N_2O Emissions. Agron. Sustain. Dev. **35** 1551 – 1559.

[121] Zhao, Q., Xiong, W., Xing, Y., Sun, Y., Lin, X., & Dong, Y. (2018). Long-Term Coffee Monoculture Alters Soil Chemical Properties & Microbial Communities. Scientific Reports. **8** 6166.

[122] Pham, T., Nguyen, N. H., Yen, P. N. D., Lam, T. D., & Le, N. T. T. (2020). Proposed Techniques to Supplement the Loss in Nutrient Cycling for Replanted Coffee Plantations in Vietnam. Agronomy. **10** 905.

[123] Tumwebaze, S. B. & Byakagaba, P. (2015). Soil Organic Carbon Stocks Under Coffee Agroforestry Systems & Coffee Monoculture in Uganda. Agriculture, Ecosystems & Environment. **216** 188 – 193.

[124] Tumwebaze, S. B. & Byakagaba, P. (2015). Soil Organic Carbon Stocks Under Coffee Agroforestry Systems & Coffee Monoculture in Uganda. Agriculture, Ecosystems & Environment. **216** 188 – 193.

ii. Pest Management

Pests and diseases can decimate coffee yields and are anticipated to increase in occurrence due to changing climate conditions[125]. Many studies highlight what farmers and researchers can do to combat pests, fungi, and diseases:

- Intercropping fruit and leguminous trees to create shaded coffee systems.
- Grafting disease and pest tolerant rootstocks onto desirable scion.
- Implementing seedling prescreening tests for resistance and tolerance to expedite research.

Brazil: The literature overwhelmingly focuses on two, though – Coffee Leaf Rust (CLR), caused by *Hemileia vastatrix*, and Coffee Berry Disease (CBD), caused by *Colletotrichum kahawae*. Left untreated, CLR and CBD can create yield losses of 10-40% and 70-80%, respectively[126]. Though it was thought that shaded production reduces disease prevalence by interrupting rainfall, which is the dispersal mechanism of CLR, shaded coffee berries don't gain any intrinsic resistance[127]. Furthermore, using shade trees to reduce the likelihood and severity of CBD actually increases fungal diseases that tend to perform better under shade.[128]

Vietnam: Pratylenchus coffeae and *Radopholus arabocoffeae* are two prevalent plant-parasitic nematodes in Vietnam that damage plants by attacking their root structure. Horticultural grafting of pest resistant or pest tolerant plants may be a solution. Grafting involves splicing together the aboveground, vegetative half of one plant, called the scion, with the belowground, rooting half of another plant, called the rootstock. Robusta cultivars 'Hong 34' and *C. liberica* var. Dewevrei are two rootstocks that exhibit good resistance and tolerance to these nematode species[129]. These cultivars, however, are not widely used due to their suboptimal quality and yield. Fortunately, grafting does not significantly affect the scion bean's chemical or organoleptic characteristics and may therefore be attempted on more desirable cultivars [130].

iii. Irrigation Management

Rainfall is a fundamental component of growing coffee, and rainfall patterns will continue to shift as climate change progresses[131]. The general trend is that dry seasons will become drier and wet seasons will become wetter[132]. Although changes in the length and intensity of rainy seasons and rainfall episodes will affect coffee growth and production, artificial irrigation can supplement periods of drought[133]. Drought tolerance has also been documented as

---

[125] Magrach, A., & Ghazoul, J. (2015). Climate and Pest-Driven Geographic Shifts in Global Coffee Production: Implications for Forest Cover, Biodiversity and Carbon Storage. *PLOS ONE*, *10*(7), e0133071. https://doi.org/10.1371/journal.pone.0133071

[126] Silva, Mario do Céu et al. (2006). Coffee Resistance to the Main Diseases: Leaf Rust & Coffee Berry Disease. Braz. J. of Plant Physiol. 18 (1) : 119 – 147.

[127] Bedimo, M. J. A., Njiayouom, I., Bieysse, D., Nkeng, M. N., Cilas, C., & Nottéghem, J. L. (2008). Effect of Shade on Arabica Coffee Berry Disease Development: Toward an Agroforestry System to Reduce Disease Impact. Phytopathology. 98: 1320 – 1325.

[128] Bedimo, M. J. A., Njiayouom, I., Bieysse, D., Nkeng, M. N., Cilas, C., & Nottéghem, J. L. (2008). Effect of Shade on Arabica Coffee Berry Disease Development: Toward an Agroforestry System to Reduce Disease Impact. Phytopathology. 98: 1320 – 1325.

[129] Trinh, P. Q., Wesemael, W. M. L., Tran, H. A., Nguyen, C. N., & Moens, M. (2012). Resistance Screening of *Coffea* spp. Accessions for *Pratylenchus coffeae* & *Radopholus arabocoffeae* in Vietnam. Euphytica. 185: 233 – 241.

[130] Villain, L., Molina, A., Sierra, S., Decazy, B., & Sarah, J. L. (2000). Effect of Grafting & Nematicide Treatments on Damage by Root-Lesion Nematodes (*Pratylenchus* spp.) to *Coffea arabica* L. in Guatemala. Nematropica. 30: 87 – 100.

[131] Konapala, G., Mishra, A. K., Wada, Y., & Mann, M. E. (2020). Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nature Communications*, *11*(1), 3044. https://doi.org/10.1038/s41467-020-16757-w

[132] *Ibid*

[133] Adhikari, U., Nejadhashemi, A. P., & Woznicki, S. A. (2015). Climate change and eastern Africa: A review of impact on major crops. *Food and Energy Security*, *4*(2), 110–132. https://doi.org/10.1002/fes3.61

a trainable gene in Robusta crops; a potential solution for areas where precipitation is predicted to decrease and irrigation is infeasible due to water scarcity[134].

Farmers can also benefit by understanding the effect of water abundance and scarcity on plant development, and then controlling the irrigation schedule accordingly. During certain growth stages, such as the one that occurs from January to April in Vietnam, irrigation is crucial for proper cherry development, though this comes after a period of intentional water stress[135]. Education on irrigation management is a worthwhile endeavor, as over-irrigating wastes water and financial resources without gaining positive yield outcomes[136]. Management resources should include the interaction of irrigation and fertilizer application and can dramatically increase farmer profit margins and thus quality of life[137]. It's important to note that some scientists disagree with the aforementioned, thinking instead that without the optimal atmospheric temperatures, manipulating water and nutrient availability have little to no impact on coffee yields[138].

iv. Shading Management

Shade trees on coffee farms are important for buffering both high and low temperatures, adding organic matter, and acting as a protective barrier during extreme weather events[139]. For example, Beer et al. (1997) found that shade trees can reduce the maximum temperature by 5.4-degrees Celsius and increase the minimum temperature by 1.5-degrees Celsius. However, shade trees can also encourage moisture retention, creating a microclimate conducive for mold growth. Pests, such as the coffee berry borer (CBB), are also drawn preferentially to the mix of environmental conditions created by a mixed crop, shaded plantation[140].

While sun-grown coffee has historically produced higher yields, shade-grown coffee has a reputation of producing higher-quality coffee. Similarly, a densely planted stand of coffee trees can positively influence flavor development, but the density must be managed so the shade trees neither overtake the coffee plants nor add unnecessary competition for ecosystem resources[141].

Shade trees can also provide supplemental income to farmers. Tree species should be selected based on the popularity of their fruit or the value of their timber. When coffee prices are low, coffee farmers can harvest the shade trees to supplement their income. Shade trees also add value by decreasing erosion, reducing greenhouse gas emissions, and increasing nutrient cycling in the soil.[142] [143]

---

[134] Menezes-Silva, P. E., Sanglard, L. M. V. P., Ávila, R. T., Morais, L. E., Martins, S. C. V., Nobres, P., Patreze, C. M., Ferreira, M. A., Araújo, W. L., Fernie, A. R., & DaMatta, F. M. (2017). Photosynthetic and metabolic acclimation to repeated drought events play key roles in drought tolerance in coffee. *Journal of Experimental Botany*, *68*(15), 4309–4322. https://doi.org/10.1093/jxb/erx211

[135] Amarasinghe, U. A., Hoanh, C. T., D'haeze, D., & Hung, T. Q. (2015). Toward sustainable coffee production in Vietnam: More coffee with less water. *Agricultural Systems*, *136*, 96–105. https://doi.org/10.1016/j.agsy.2015.02.008

[136] *Ibid*

[137] *Ibid*

[138] Kath, J, Byrareddy, VM, Craparo, A, et al. Not so robust: Robusta coffee production is highly sensitive to temperature. *Glob Change Biol*. 2020; 26: 3677– 3688. https://doi.org/10.1111/gcb.15097

[139] *Importance of Shade Trees in Coffee | Uganda Coffee Development Authority*. (n.d.). Retrieved March 11, 2021, from https://ugandacoffee.go.ug/importance-shade-trees-coffee

[140] *Ibid*

[141] *Sun-grown vs. shade-grown: How it impacts the environment and the farmers*. (n.d.). De La Gente. Retrieved March 11, 2021, from https://www.dlgcoffee.org/news/2017/4/6/coffee-cultivation-sun-grown-shade-grown-and-how-it-impacts-the-environment-and-the-farmers

[142] Beer, J., Muschler, R., Kass, D., & Somarriba, E. (1997). Shade management in coffee and cacao plantations. *Agroforestry Systems*, *38*(1), 139–164. https://doi.org/10.1023/A:1005956528316

v. Technology and Productivity Investment

Coffee production can be enhanced with increased productivity capacity from technological investments. This can occur in the growth, as well as production, phase, and may include advancements such as mechanically harvesting. Other investments can occur in breeding pest and drought resistant and tolerant plants to create replicable hybrids for scaled planting which would drastically reduce the plants susceptibility to these disastrous factors and are mentioned above. Some work has also documented the success of crop breeding for temperature tolerance[74].

Brazil's crop production is vulnerable to temperature and precipitation change and its increase in recent years is strongly correlated with the adoption of new technologies[170]. In Brazil, producer investments that began in 1984 resulted in a 33.4% productivity increase in 2016. The most obvious advancement has been the ability to grow more coffee plants per hectare. This competitive advantage actually resulted from the end of government intervention. The adoption of technology and management innovation led them to lower costs of production which were amplified by economies of scale. Internal management and product differentiation are also avenues through which Brazilian coffee farmers have reaped success.

Access to credit, education, and technical support and resources are necessary precursors to investment in the management techniques described above[144]. With access to capital and other resources, nations can increase their yield on existing growing areas, without expanding production into forested or protected land. National and cooperative structures, such as subsidies, price floors, market access, and forest protections, can facilitate this and prevent the necessity of land clearing to meet current demand under suboptimal climate conditions, as well as protect forested land from being converted. Such improvements do not disqualify such land clearing to occur, but rather provide the opportunity to optimize currently planted areas and disincentivize expansion into unharvested areas.

b. Final Considerations

Substantial work has been done that can be incorporated into a more sophisticated model than was possible in our project. Published literature by Jarrod Kath, for example, may be extremely illuminating for predicting precise yield estimates, as the author outlines the impact of different temperatures coupled with other conditions during different production stages. The impact of CO_2 levels is especially interesting as existing studies suggest this presence may be able to offset decreases in yield caused by increasing temperatures. Different climatic and CO_2 conditions influence plant physiological pathways differently during different times of day, and while the plant can sustain higher temperatures, it is believed that overall yields may not[145]. Finally, research into developing and scaling ”climate-smart” tolerant plants to numerous sub-optimal climate factors may be a worthwhile investment[146].

This report has placed emphasis on potential production instead of actual production. We found that potential production is projected to remain high through 2050, though this ignores transaction costs. Shifting cultivation takes time and is resource intensive. The future of actual

[144] Volsi, B., Telles, T. S., Caldarelli, C. E., & da Camara, M. R. G. (2019). The dynamics of coffee production in Brazil. *PLoS ONE*, *14*(7). https://doi.org/10.1371/journal.pone.0219742
[145] Kath, J, Byrareddy, VM, Craparo, A, et al. Not so robust: Robusta coffee production is highly sensitive to temperature. *Glob Change Biol*. 2020; 26: 3677– 3688. https://doi.org/10.1111/gcb.15097
[146] Thioune, E.-H., McCarthy, J., Gallagher, T., & Osborne, B. (2017). A humidity shock leads to rapid, temperature dependent changes in coffee leaf physiology and gene expression. *Tree Physiology*, *37*(3), 367–379. https://doi.org/10.1093/treephys/tpw129

production can be seen in this past year with the disruptions posed by the Covid 19 pandemic. This was a global event that has had consequences through the entire coffee value chain, and climate change will arguably disrupt supply chains in a similar way. Covid-19 has shown corporations that they must safe-guard against supply disruptions and strengthen its value chain. We hope the pandemic has served as a catalyst for immediate and exceptional action to mitigate and adapt changing climate conditions (see Appendix).

c. Recommendations

With this information and the below final recommendations, CI can approach their partners to engage in actionable discussion. We believe that increasing productivity and resource efficiency may help lessen likelihood of potential supply gaps without converting forested or protected land for production.

Quantifying steps:

- Use suitable land calculations to illuminate most impacted regions and potentials for cultivation mitigation. Map current coffee farm land on top of the suitable area to understand how many farmers will fall out of the suitable land area and be forced to move their farms or in the worst case, leave the industry altogether. CI should work with the World Cocoa Foundation (WCF) who have already mapped many of the cocoa farmer locations and could share this expertise.[147]
- CI should continue to gathering data and when possible, fund studies to quantify parameters associated with concrete impact to fill in the data gaps and move closer to a more robust estimated supply number.
- Once all data is available and gathered, CI should work with an analytics program like *Crystal Ball* to model parameter distributions of expected outcomes along with the likelihood distribution. This tool also allows parameters to be linked so their correlation is taken into account. This would consider many of our limitations.
- This methodology can be applied to cocoa and rubber and illuminate the unique challenges for the continued production of those commodities.

Partner Steps:

- CI needs strong quantitative data to show their partners. For most parameters, we have only a qualitative assessment of whether the parameter would weakly, moderately, or strongly impact the supply of coffee into 2050. CI should still take this assessment and use it to incentivize their partners to invest in the management strategies described above. It should be stressed that these strategies will help their partners meet the future demand of coffee while preventing the conversion of forested and/or protected land into cultivated land.
- Use quantitative data from suitable land calculations to make an argument for which countries will be most impacted from this data. This could help incentivize partners to diversify their supply into different areas that are projected to have suitable land into 2050 or vertically integrate their operations to have increased control over future supply.

Farmer steps:

[147] *Enhancing traceability and professionalizing cooperatives – an example of Cémoi in Côte d'Ivoire*. (2018). IDH - the Sustainable Trade Initiative. Retrieved March 11, 2021, from https://www.idhsustainabletrade.com/news/enhancing-traceability-and-professionalizing-cooperative-an-example-of-cemoi-in-cote-divoire/

- CI should work with their partners and supply chains to develop best practices for farmers. These best practices should be as specific to the area where the farmer is located. Farmers need support but general ideas over how to best grow coffee won't be enough. They need ideas that stem from how coffee reacts to specific conditions in their country. The WCF can again act as a model as they have already created a similar program for their cocoa farmers and have developed a tool allowing farmers to enter their coordinates and receive bioclimatic information and climate change impacts[148].

d. Concluding Remarks

The initial goal of this project was to create an objective methodology to measure global coffee supply for Conservation International to incentivize investments from their corporate partners to meet projected demand, without encroaching on forested and/or protected land. If we found that changing climate conditions resulted in disruptions of future coffee production, our work would ideally incentivize Sustainable Coffee Challenge partners to collaborate to invest in innovation and devise additional solutions to ensure an ample supply of coffee for their companies. However, due to lack of available data and published yield impacts for a large majority of our parameters, this did not come to fruition. Ultimately, a lack of data and in particular, quantitative data, inhibited the model from being as robust as initially desired. To best satisfy the original objective of this project, the bioclimatic parameters with the most-sound information were quantified and modeled, and their isolated impacts on future coffee supply were considered. As there are many other parameters and confounding effects of parameter interactions on actual coffee production, this report aimed to provide some description of these variables and the direction and magnitude of their impact in a qualified analysis (see Appendix Figure 1). Additionally, information was compiled regarding management practices that mitigate climate risk and support farmers as they adapt to changing climate and socioeconomic conditions. The successful implementation of these practices may better secure future coffee supply.

[148] *Clima App*. (n.d.). Retrieved March 11, 2021, from http://cafeclima.kronoscode.com/

X. Appendix

I. Qualitative results

	Brazil	Colombia	Ethiopia	Honduras	India	Indonesia	Vietnam
Forested/Protected Land	-1	-2	-1	-2	-2	-3	-3
Temperature	-2	-2	-1	-2	-2	-2	-2
Coffee Berry Borer	-2	-1	-1	-2	-2	-3	NA
Coffee Leaf Miner	-2 to -3	-1	NA	-1	NA	NA	NA
Coffee Leaf Rust	-2	-2	-3	-2	-2	-	-
Coffee Berry Disease	NA	NA	-3	NA	NA	NA	NA
Urbanization	-1	-1	-1	-1	-1	-1	-1
Contracts and Pricing	+1	+1	+1	+1	+1	+1	+1
Certifications	+1	+1	+1	+1	+1	+1	+1
Competing crops	-1	-	-	-	-1	-1	-1
Extreme Weather	-3	-3	-3	-3	-3	-3	-3
National Policies	+1	+1 to 3	+1	+2	+1	+1 to +2	+1 to 2

Figure 1: Qualitative measure of parameters based on direction and magnitude

II. Specific Coffee Berry Borer Methodology for Colombia & Ethiopia

Coffea arabica is native to the high-altitude regions of Southwestern Ethiopia, where it grows at elevations ranging from 1,600 to 2,800 meters above sea level (m.a.s.l.) and temperatures ranging from 18 to 21°C[149]. According to Jaramillo et al. (2009), the coffee berry borer (CBB), *Hypothenemus hampei*, is the most significant coffee pest globally. Before 1984, *H. hampei* was absent from Ethiopia because it was too cold[150]. In three papers, authored in 2009, 2011, and 2017, Jaramillo and her colleagues try to map the thermal tolerance of the coffee berry borer to changes in climate, define its impact, and provide guidance for mitigation strategies[151] [152]. The coffee berry borer has lower and upper developmental thermal thresholds of 14.9°C and 32°C, respectively. Using a predictive model, Jaramillo et al. (2009) found that, for every 1°C increase in the thermal optimum[1] (T_{opt}), up to 26.7°C, the intrinsic rate of increase[2] (r_{max}) would rise by an average of 8.5%. To quantify CBB's impact on global coffee supply, the model assumes that an increase in r_{max} is the same as an equivalent decrease in production. In other words, the model assumes that for every 1°C increase in temperature, up to 26.7°C, a given country will see a corresponding decrease in supply of 8.5% from the baseline year. The baseline temperature is an average of the ten most recent years for which there is data. If the model predicts a future temperature below the baseline temperature, CBB's impact is assumed to be zero; there is no 'earning back' yield beyond the baseline quantity. It's important to note that every country except, potentially, Papua New Guinea has acknowledged the presence of CBB in their coffee plantations, and every country suffers pest damage from CBB at different levels[153]. For example, according to Jaramillo et al. (2009), the bioclimatic conditions in Columbia, Kenya, Tanzania, and Ethiopia produce 3.4, 3.1, 3.1, and 1.3 generations per year of CBB,

---

[149] Jaramillo, J., Chabi-Olaye, A., Kamonjo, C., et al. (2009). Thermal Tolerance of the Coffee Berry Borer *Hypothenemus hampei*: Predictions of Climate Change Impact on a Tropical Insect Pest. *PLoS ONE,* 4(8): e6487.
[150] Jaramillo, J., Chabi-Olaye, A., Kamonjo, C., et al. (2009). Thermal Tolerance of the Coffee Berry Borer *Hypothenemus hampei*: Predictions of Climate Change Impact on a Tropical Insect Pest. *PLoS ONE,* 4(8): e6487.
[151] Jaramillo, J., Muchugu, E., Vega, F.E., et al. (2011). Some Like It Hot: The Influence & Implications of Climate Change on Coffee Berry Borer (*Hypothenemus hampei*) & Coffee Production in East Africa. PLoS ONE. 6(9): e24528.
[152] Atallah, S. S., Gómez, M. I., & Jaramillo, J. (2017). A Bioeconomic Model of Ecosystem Services Provision: Coffee Berry Borer & Shade-Grown Coffee in Columbia. Ecological Economics. **144** 129 – 138.
[153] Baker, Peter. (2016). *Hypothenemus hampei (coffee berry borer)*. Retrieved April 21, 2021, from https://www.cabi.org/isc/datasheet/51521

respectively. However, the model ignores country-specific differences because there is no up-to-date, comprehensive data about the severity of CBB in different countries, only presence-absence data.

The regression model averages historic temperature data from January, 2007 to December, 2016 to create a 10-year baseline temperature of 23.44°C for future comparisons. The impact of CBB is presented in decadal increments starting in 2020. The expected outcome is calculated as the product of the likelihood of impact and the predicted impact on yield. The likelihood of impact is calculated as the number of months with temperatures exceeding the baseline in that decade, divided by the number of months in that decade. Since Conservation International is looking for the best- and worst- case scenarios, the appropriate number for their work is just the predicted impact on yield

III. Certification

Many consumers believe in their purchasing power and choose to buy into the desirable social and ecological standards set by organizations like Fairtrade, though they fail to see the limited reach and impact of the certification[154]. Cooperatives like the Colombian Coffee Growers Federation took advantage of this long-term trend of purchasing power by helping its farmers develop higher value coffees, such as sustainably certified coffee and coffee with geographically unique cup profiles. This strategy worked to great effect with the export of 'origin' coffees tripling in nine years and certified coffees increasing 150-fold in the same time frame. However, this success created a geographic shift in where coffee was produced within Colombia because only certain regions produced desirable cup profiles[155]. As a result, consumer demand for niche coffees drove coffee production away from certain regions and into others. Certifications can have positive benefits, as Fairtrade and UTZ require a complete absence of forced and child labor as one component for a producer to become certified.

Ho et al. (2018) and Nguyen et al. (2015) performed independent literature reviews to understand how certification affects farmer livelihood and long-term farm viability[156]. Both papers find conflicting results: decreased and increased input costs, higher and lower revenue, greater and the same conserved biodiversity. Ho et al. (2018) also collected data on fertilizer application, water consumption, and pesticide use on conventional and sustainable-certified coffee farms in Vietnam. Conventional, organic, and organic-Fairtrade cooperatives will have marginal differences for failing farms[157]. One consideration is global price and the dependence on this price[158]. Fair trade can be attractive to coffee farmers when prices for conventional coffee are extremely low since fair trade coffee is sold at a premium. However, it is harder to predict the impacts of fair trade on maintaining reasonable prices in the long-run[159]. In the case of Fairtrade (FLO), certified farmers benefit from a guaranteed floor price[160]. Collectively, the price

[154] Fridell, G. (2014). Fair Trade Slippages & Vietnam Gaps: The Ideological Fantasies of Fair Trade Coffee. Third World Quarterly. 35 (7) : 1179 – 1194.

[155] Rueda, X. & Lambin, E. F. (2013). Linking Globalization to Local Land Uses: How Eco-Consumers & Gourmands are Changing the Columbian Coffee Landscapes. World Development. 41: 286 – 301.

[156] Ho, T. Q., Hoang, V., Wilson, C., & Nguyen, T. (2018). Eco-Efficiency Analysis of Sustainability-Certified Coffee Production in Vietnam. Journal of Cleaner Production. 183: 251 – 260.

[157] Fridell, G. (2014). Fair Trade Slippages & Vietnam Gaps: The Ideological Fantasies of Fair Trade Coffee. Third World Quarterly. 35 (7) : 1179 – 1194.

[158] Valkila, J. (2009). Fair Trade organic coffee production in Nicaragua - Sustainable development or a poverty trap?. *Ecological Economics*, 68 (12): 3018-3025. Retrieved from: https://doi.org/10.1016/j.ecolecon.2009.07.002.

[159] Valkila, J. (2009). Fair Trade organic coffee production in Nicaragua - Sustainable development or a poverty trap?. *Ecological Economics*, 68 (12): 3018-3025. Retrieved from: https://doi.org/10.1016/j.ecolecon.2009.07.002.

[160] May, P. H., Mascarenhas, G. C. C., & Potts, J. (2004). Sustainable Coffee Trade: The Role of Coffee Contracts. International Institute for Sustainable Development.

premium, eco-efficiency, and healthier ecosystem associated with certification should create a positive feedback loop that supports coffee production in the future.

For countries that have established good practices before layering on sustainable certifications benefit as their purchasing decisions have a positive impact and customers can be persuaded to pay a premium[161]. For farmers who want to transition to sustainable production practices[162] and become certified, the practices can improve farm efficiency under the right circumstances.

Gaitán-Cremaschi et al. (2018) supports these findings by saying, "The main source *NI* is the allocative inefficiency..., rather than pure technical inefficiency or scale inefficiency[163]." Of course, there are savings associated with the economies of scale found in different production models[164].

This is relevant to coffee supply because most certification groups demand or encourage the responsible use of natural resources. If the farm transitions to sustainable practices, implementation could improve farm profitability and bring them more in line with certification guidelines (Figure 2). By 2015, half of the farmer cooperatives in Brazil were certified fair-trade and Brazilian scientific research suggest that certification has contributed to the improvement of farms and increased internationalization[165]. According to World Bank (2013)[166], local coffee producers have improved the harvest and increased the export of fair-trade certified grains for 8,000 rural families

Besides the fair-trade certificate, in-house certification and environmental practices adopted by farms allow better environmental management of their operations and can improve total production and the share of the market held by Brazil giving them greater bargaining power[167]. Additionally, some country-specific certificates such as Legal Reserves set by the Brazilian Forest Code has encouraged farmers to restore ecosystems that were lost due to agriculture. [168]

Silva et al. (2006) outlines a few of the many pests and diseases faced by the coffee producing world (Table 1)[169].

Common Name	**Scientific Name**	**Spread**
Fungal		

[161] Fridell, G. (2014). Fair Trade Slippages & Vietnam Gaps: The Ideological Fantasies of Fair Trade Coffee. Third World Quarterly. 35 (7) : 1179 – 1194.
[162] Le, Q. V., Jovanovic, G., Le, D., & Cowal, S. (2020). Understanding the Perceptions of Sustainable Coffee Production: A Case Study of the K'Ho Ethnic Minority in a Small Village in Lam Dong Province of Vietnam. Sustainability. 12.
[163] Gaitán-Cremaschi, D., van Evert, F. K., Jansen, D. M., Meuwissen, M. P., & Lansink, A. G. J. M. O. (2018). Assessing the Sustainability Performance of Coffee Farms in Vietnam: A Social Profit Inefficiency Approach. Sustainability. 10.
[164] Anh, N. H., Bokelmann, W., Thuan, N. G., Nga, D. T., & Nguyen, V. M. (2019). Smallholders' Preferences for Different Contract Farming Models: Empericial Evidence from Sustainable Certified Coffee Production in Vietnam. Sustainability. 11.
[165] World Wildlife Fund (WWF). (2015). Brazil's new Forest Code: A guide for decision-makers in supply chains and governments. Retrieved from: http://assets.wwf.org.uk/downloads/wwf_brazils_new_forest_code_guide_1.pdf?_ga=2.126793997.163061138.1570106353-1735305701.1570106353
[166] World Bank. (2013). Support to coffee farmers awakens development in rural Sao Paulo, Brazil. Retrieved from: https://www.worldbank.org/en/news/feature/2013/09/25/Brazil-fair-trade-coffee-farming

[167] Giuliani, E., Ciravegna, L., Vezzulli, A., Kilian, B. (2017). Decoupling Standards from Practice: The Impact of In-House Certifications on Coffee Farms' Environmental and Social Conduct. World Development, 96: 294-314. Retrieved from: https://doi.org/10.1016/j.worlddev.2017.03.013
[168] Pinto, L.F.G., Gardner, McDermott, C.L., & Ayub, K.O.L. (2014). Group certification supports an increase in the diversity of sustainable agriculture network–rainforest alliance certified coffee producers in Brazil. *Ecological Economics*, 107: 59-64. Retrieved from: https://doi.org/10.1016/j.ecolecon.2014.08.006
[169] Silva, Mario do Céu et al. (2006). Coffee Resistance to the Main Diseases: Leaf Rust & Coffee Berry Disease. Braz. J. of Plant Physiol. 18 (1) : 119 – 147.

Coffee Leaf Rust (CLR)	*Hemileia vastatrix*	
Other Rust Diseases (Powdery, Yellow Rust, or Grey Rust)	*Hemilieia coffeicola* Maubl/Rog	West African *C. canephora*
Coffee Berry Disease (CBD)	*Colletotrichum kahawae [coffeanum]* *Colletotrichum gloeosporioiedes* Penz *Colletotrichum acutatum* Simmond	Africa
Coffee Wilt Disease	*Fusarium xylarioides* Steyaert	Central/West Africa; A+R
Coffee Bark Disease	*Fusarium stilboides* Wollenw	Ethiopia, Kenya, Malawi, Tanzania
Brown Eye Spot/Berry Blotch Disease	*Cercospora coffeícola* Berk/Cooke	Nurseries/Plantations
American Leaf Spot	*Mycena citricolor* Sacc.	N/S America
Bacterial		
Halo Blight	*Pseudomonas syringae*	Brazil, Kenya, Uganda, China
Coffee Leaf Scorch	*Xilella fastidiosa* Wells	Brazil, Costa Rica
Viral		
Coffee Ringspot Virus (CoRSV)	*Brevipalpus phoenicis* [Vector - Mite]	Brazil, Costa Rica, Philippines?
Other		
Plant-Parasitic Nematode	*Pratylenchus coffeae*	Vietnam
Plant-Parasitic Nematode	*Radopholus arabocoffeae*	Vietnam
Stem Borer	*Xylotrechus quadripes*	
Sharpshooter Leafhooper [Vector]	*Dilobopterus cortalimai*	

Source: Silva (2006) & Trinh (2012)

Table 6: Comparative analysis of standard and alternative coffee contracts based on sustainability and market-driven criteria.

CHARACTERISTICS OF COFFEE CONTRACTS	STANDARD	ALTERNATIVE		
		FAIR TRADE	STARBUCKS	UTZ KAPEH
DRIVERS **SUSTAINABILITY DIMENSIONS**	Market price and product quality driven	Socially driven; ILO principles; Process-oriented	Environmentally and quality driven	Code of Conduct Eurep-GAP SA 8000
ECONOMIC CRITERIA	**Quality and origin (Must)**	*Obligatory* **(Must)**	*Obligatory* **(Must)**	*Recommended* **(Should)**
Long-term contracts	No	Yes	Yes	Yes
Preferred suppliers	No	Yes	Yes	Yes
Differential pricing	Product and origin related	Floor price	Point system for price differential	Sustainability differential
Community premium	No	Yes	No	No
Advance on sales	No	Yes	No	No
Coverage of certification costs	No	Yes	No	No
Traceability and transparency	Low	High	High	High
Compatibility with mainstream trade channels	High	Low	Moderate	Moderate
Impacts on macroeconomic conditions	Moderate	Low	Low	Low
Market penetration	High	Low (Niche-oriented)	Medium (Brand-specific)	Low/Medium
Mainstream market potential	High (this is the mainstream...)	Low	Medium	High
SOCIAL CRITERIA	*Not Included* **(Free)**	*Obligatory* **(Must)**	*Recommended* **(Should)**	*Obligatory* **(Must)**
Salaries and benefits	No	Yes	Yes	Yes
Labour conditions	No	Yes	Yes	Yes
Living conditions	No	Yes	Yes	Yes
Gender equity; respect minority rights	No	Yes	Not specified	Not specified
Restriction on child labour use	No	Yes	Not specified	Yes
Democracy community self-management	No	Yes	Not specified	Yes
ENVIRONMENTAL CRITERIA	*Not Included* **(Free)**	*Recommended* **(Should)**	*Obligatory* **(Must)**	*Obligatory* **(Must)**
Water management	No	Yes	Yes	Yes
Soil conservation	No	Yes	Yes	Yes
Forests and biodiversity	No	Yes	Yes	Yes
Pest control	No	Yes	Yes	Yes
Energy use	No	Yes	Yes	Yes
Waste management	No	Yes	Yes	Yes

Figure 4: May, 2004

Coffee breeding work began in Kenya in 1924. Today, multiple institutions focus on finding or creating and then testing new hybrids that combine high yield with superior quality and resistance to diseases like CLR and CBD[170]. However, progress can be slow if scientists have to

[170] Gimase, J. M., Omondi, C. O., & Kathurima, C. W. (2015). Coffee Improvement by Interspecific Hybridization: A Review. Journal of Agricultural & Crop Research. **3** (3) : 41 – 46.

wait months or years to test a new cultivar's susceptibility to common diseases. Two papers by Van der Vossen et al. (1976, 1980) outline how coffee seedlings as young as a few weeks can be more reliable than older plants at indicating future disease resistance. "The results of this study have demonstrated clearly that the hypocotyl preselection test, by which 5-6 weeks old coffee seedlings are inoculated with a spore suspension of the pathogen, gives reliable information about mature plant resistance to coffee berry disease... It greatly improves the efficiency of the breeding program making it possible to screen thousands of plants… for resistance to CBD at a very early stage in the laboratory.[171] [172]

Capa et al. (2015) found that a low fertilization rate was defined as 70, 22, and 31 kg of nitrogen, phosphorous, and potassium per hectare per year for the first year, respectively, and 200, 65, and 62 kg for the second year, respectively[173]. The Capa et al. (2015) findings in Ecuador are supported by later findings by Byrareddy et al. (2019) in Vietnam and Indonesia. Byrareddy found that a portion of farmers in SE Asia apply fertilizer at up to half the rate as others but achieve the same or higher yields. For example, farmers in the Gia Lai and Lam Dong provinces of Vietnam achieved similar yields but reported using between 88 and 176 kg of phosphorous per hectare. This and other similar findings in the study suggest the potential to reduce the quantity of fertilizer without dramatically reducing yield.

Table 2 Gross income, costs, net income, and production to nitrous oxide emissions ratio of coffee production in the different treatments (control, low, medium, and high fertilization rates) across the 2 years of the field experiment (2011 and 2012)

Treatment	Gross income (USD ha^{-1})	Costs (USD ha^{-1})	Net income (USD ha^{-1})	Production-emission ratio
Control	6433	2909	3524a±571	731b±114
Low	11,430	3824	7606b±357	603b±106
Medium	14,517	4331	10,187c±123	208a±26
High	15,526	4942	10,584c±661	188a±11

Mean±standard deviation, n=3. Values followed by the same lowercase letter within the same period of the experiment are not significantly different among treatments (P<0.05)

Figure 5: Capa et al. (2015)

IV. Baseline Potential Encroachment Flexibility:

The below forecast show the flexibility that each country (the remaining five we studied) has available in order to avoid encroachment on forested and/or protected land at a baseline (no parameters are considered). They are ordered from least flexible to most flexible.

[171] Van der Vossen, H. A. M. & Walyaro, D. J. (1980). Breeding for Resistance to Coffee Berry Disease in *Coffea Arabica* L. II. Inheritance of the Resistance. Euphytica. **29.** 777 – 791.
[172] Van der Vossen, H. A. M., Cook, R. T. A., & Murakaru, G. N. W. (1976). Breeding for Resistance to Coffee Berry Disease Caused by *Colletrotrichum Coffeanum Noack* (Sensu Hindorf) in *Coffea Arabia* L. I. Methods of Preselection for Resistance. Euphytica. **25.** 733 – 745.
[173] Capa, D., Pérez-Esteban, J., & Masaguer, A. (2015). Unsustainability of Recommended Fertilization Rates for Coffee Monoculture Due to High N_2O Emissions. Agron. Sustain. Dev. **35** 1551 – 1559.

	Forecast for Indonesia's Arabica and Robusta Production 2020-2050 (in millions)											
	2020-2030				2031-2040				2041-2050			
	Arabica		Robusta		Arabica		Robusta		Arabica		Robusta	
	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best
Total Potential Suitable Production (kg)	1,623.1	1,623.1	24,963.5	24,963.5	1,645.8	1,687.0	23,209.6	23,789.9	1,511.7	1,695.9	19,253.6	21,599.6
BAU Demand	0.1	0.1	0.6	0.5	0.1	0.1	0.8	0.6	0.1	0.1	1.1	0.6
Supply Gap/Excess	1,623.0	1,623.0	24,963.0	24,963.0	1,645.8	1,686.9	23,208.9	23,789.3	1,511.6	1,695.8	19,252.6	21,598.9
Forested (not protected)	1,065.1	1,065.1	17,941.2	17,941.2	1,082.9	1,109.9	16,538.0	16,951.5	997.4	1,118.9	13,566.5	15,219.5
Protected (not forested)	11.2	11.2	183.8	183.8	13.5	13.8	138.9	142.4	14.5	16.3	81.1	90.9
Forested and Protected	427.8	427.8	4,729.3	4,729.3	441.7	452.8	4,664.9	4,781.5	413.5	463.9	4,156.5	4,663.0
Land (ha) Available (Encroached)	0.2	0.2	3.7	3.7	0.2	0.2	3.1	3.1	0.2	0.2	2.5	2.5
% Flexibility	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%

Figure A. Baseline potential forested/protected land encroachment without factoring in any parameter impacts for Indonesia’s Arabica and Robusta production

	Forecast for Colombia's Arabica and Robusta Production 2020-2050 (in millions)											
	2020-2030				2031-2040				2041-2050			
	Arabica		Robusta		Arabica		Robusta		Arabica		Robusta	
	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best
Total Potential Suitable Production (kg)	7,834.9	7,834.9	5,219.0	5,219.0	7,832.8	8,224.4	4,984.5	5,233.8	7,084.7	8,613.6	4,276.4	5,199.2
BAU Demand	0.9	0.8	-	-	1.3	0.9	-	-	1.7	1.0	-	-
Supply Gap/Excess	7,834.0	7,834.1	5,219.0	5,219.0	7,831.5	8,223.5	4,984.5	5,233.8	7,083.0	8,612.6	4,276.4	5,199.2
Forested (not protected)	5,531.2	5,531.2	3,861.2	3,861.2	5,545.7	5,823.0	3,681.4	3,865.4	5,032.0	6,117.9	3,151.8	3,831.9
Protected (not forested)	22.5	22.5	3.2	3.2	24.6	25.8	2.3	2.4	24.3	29.5	1.2	1.5
Forested and Protected	626.6	626.6	394.1	394.1	614.2	644.9	404.4	424.6	543.3	660.5	376.1	457.3
Land (ha) Available (Encroached)	2.1	2.1	1.2	1.2	2.1	2.2	1.1	1.2	1.9	2.3	1.0	1.2
% Flexibility	21%	21%	18%	18%	21%	21%	18%	18%	21%	21%	17%	17%

Figure B. Baseline potential forested/protected land encroachment without factoring in any parameter impacts for Colombia’s Arabica and Robusta production

	Forecast for India's Arabica and Robusta Production 2020-2050 (in millions)											
	2020-2030				2031-2040				2041-2050			
	Arabica		Robusta		Arabica		Robusta		Arabica		Robusta	
	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best
Total Potential Suitable Production (kg)	84.1	84.1	4,227.4	4,227.4	56.8	59.6	3,833.6	4,025.2	24.2	29.4	3,076.5	3,740.4
BAU Demand	0.1	0.1	0.2	0.2	0.1	0.1	0.3	0.2	0.2	0.1	0.5	0.3
Supply Gap/Excess	84.0	84.0	4,227.1	4,227.2	56.7	59.5	3,833.2	4,025.0	24.0	29.3	3,076.0	3,740.1
Forested (not protected)	45.2	45.2	2,000.2	2,000.2	30.3	31.8	1,893.6	1,988.3	12.5	15.2	1,607.2	1,954.0
Protected (not forested)	2.9	2.9	221.7	221.7	1.9	1.9	198.6	208.5	0.6	0.7	156.6	190.4
Forested and Protected	15.9	15.9	511.9	511.9	10.0	10.5	504.9	530.1	3.2	3.8	449.8	546.9
Land (ha) Available (Encroached)	0.0	0.0	1.7	1.7	0.0	0.0	1.4	1.5	0.0	0.0	1.0	1.2
% Flexibility	24%	24%	35%	35%	26%	26%	32%	32%	32%	32%	28%	28%

Figure C. Baseline potential forested/protected land encroachment without factoring in any parameter impacts for India’s Arabica and Robusta production

	Forecast for Honduras' Arabica and Robusta Production 2020-2050 (in millions)											
	2020-2030				2031-2040				2041-2050			
	Arabica		Robusta		Arabica		Robusta		Arabica		Robusta	
	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best
Total Potential Suitable Production (kg)	4,425.5	4,425.5	2,817.3	2,817.3	3,827.2	4,114.3	2,677.8	2,878.6	2,867.4	3,696.6	2,283.9	2,944.5
BAU Demand	0.5	0.4	-	-	0.7	0.5	-	-	0.9	0.5	-	-
Supply Gap/Excess	4,425.0	4,425.1	2,817.3	2,817.3	3,826.6	4,113.8	2,677.8	2,878.6	2,866.4	3,696.1	2,283.9	2,944.5
Forested (not protected)	2,434.5	2,434.5	1,165.0	1,165.0	2,171.7	2,334.5	1,175.5	1,263.7	1,703.2	2,195.8	1,074.0	1,384.6
Protected (not forested)	31.7	31.7	66.9	66.9	26.2	28.2	51.6	55.5	18.3	23.6	31.6	40.7
Forested and Protected	411.9	411.9	773.3	773.3	374.2	402.3	674.1	724.6	301.1	388.1	511.2	659.0
Land (ha) Available (Encroached)	1.4	1.4	0.7	0.7	1.1	1.1	0.7	0.7	0.8	0.8	0.6	0.6
% Flexibility	35%	35%	29%	29%	33%	33%	29%	29%	29%	29%	29%	29%

Figure D. Baseline potential forested/protected land encroachment without factoring in any parameter impacts for Honduras’ Arabica and Robusta production

Forecast for Ethiopia's Arabica and Robusta Production 2020-2050 (in millions)												
	2020-2030				2031-2040				2041-2050			
	Arabica		Robusta		Arabica		Robusta		Arabica		Robusta	
	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best
Total Potential Suitable Production (kg)	14,080.9	14,080.9	916.4	916.4	15,297.8	16,062.7	1,019.0	1,070.0	15,052.0	18,300.1	1,024.1	1,245.0
BAU Demand	0.5	0.5	-	-	0.7	0.5	-	-	1.0	0.6	-	-
Supply Gap/Excess	14,080.4	14,080.5	916.4	916.4	15,297.1	16,062.2	1,019.0	1,070.0	15,051.0	18,299.5	1,024.1	1,245.0
Forested (not protected)	2,316.8	2,316.8	84.5	84.5	2,383.5	2,502.7	96.3	101.1	2,222.9	2,702.5	98.9	120.2
Protected (not forested)	47.6	47.6	33.6	33.6	45.4	47.7	33.4	35.1	38.9	47.3	30.1	36.6
Forested and Protected	11.7	11.7	1.9	1.9	15.0	15.8	2.1	2.2	16.8	20.5	2.2	2.7
Land (ha) Available (Encroached)	14.9	14.9	1.0	1.0	16.3	17.1	1.1	1.2	16.2	19.7	1.1	1.4
% Flexibility	83%	83%	87%	87%	84%	84%	87%	87%	85%	85%	87%	87%

Figure E. Baseline potential forested/protected land encroachment without factoring in any parameter impacts for Ethiopia's Arabica and Robusta production

V. National Policies

In Brazil, Arabica production is located in the main coffee-growing cluster of states led by Minas Gerais[174]. Brazil has the opportunity to drastically increase its agricultural production without new deforestation[175], due to a sufficient total area of accumulated cleared and underutilized land[176]. In addition, producers and companies have made a series of voluntary commitments to source deforestation-free commodities, e.g. Consumer Goods Forum (CGF, 2019), the Tropical Forest Alliance (TFA, 2020, 2019), the New York Declaration on Forests (NYDF, 2019), the Amsterdam Declaration Partnership (AD-Partnership, 2015) and the Soy and Beef Moratoriums.

VI. Coffee Pricing

Export price fluctuations can provide insight to understand the relationship between coffee price and production. In the early 2000s, a rapid decline in coffee prices occurred due to the dissolution of the International Coffee Agreement, a regulating document, generating widespread impacts across coffee-producing regions[177] but in particular impacting smallholder farmers[178]. This deregulation resulted in price volatility and drastically decreased producer income[179].

Coffee is produced by smallholder farmers who usually have both short- and long-run production strategies to overcome the risk of price fluctuations[180]. First are the individual-level cost reduction strategies. For example, in 1990-2000 Vietnam where smallholders accounted for 80% of production, Ha and Shively (2008)[181] estimated that small farmers could eliminate fertilizer by around 11%, eliminate irrigation by around 6.6%, and remove coffee production by 8% without having a long-term impact on their revenue. Second, farmers could make changes in their planted area, crop mix, introduce alternative crops, and engage in organic coffee production

[174] Conservation International. (2015). Coffee in the 21st Century: Will Climate Change and Increased Demand Lead to New Deforestation?. Retrieved from: https://www.conservation.org/docs/default-source/publication-pdfs/ci-coffee-report.pdf
[175] Chambers, J.Q., & Artaxo, P. (2017). Deforestation size influences rainfall. Nature Climate Change 7: 175–176. Retrieved from: https://doi.org/10.1038/nclimate3238
[176] Strassburg, B.B.N., Latawiec, A.E., Barioni, L.G., Nobre, C.A., da Silva, V.P., Valentim, J.F., Vianna, M., & Assad, E.D. (2014). When enough should be enough: improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Science,* 28: 84–97. Retrieved from: https://doi.org/10.1016/j.gloenvcha.2014.06.001
[177] Eakin, H., Tucker, C. & Castellanos, E. (2006). Responding to the coffee crisis: a pilot study of farmers' adaptations in Mexico, Guatemala and Honduras. *Geographical Journal,* 172(2): 156-171. Retrieved from: https://doi.org/10.1111/j.1475-4959.2006.00195.x
[178] Ha, D.T., & Shively, G. (2008). Coffee Boom, Coffee Bust and Smallholder Response in Vietnam's Central Highlands. *Review of Development Economics,* 12(2): 312-326. Retrieved from: https://doi-org.proxy.lib.duke.edu/10.1111/j.1467-9361.2007.00391.x
[179] Volsi, B., Telles, T. S., Caldarelli, C. E., & da Camara, M. R. G. (2019). The dynamics of coffee production in Brazil. *PLoS ONE*, *14*(7). https://doi.org/10.1371/journal.pone.0219742
[180] Eakin, H., Tucker, C. & Castellanos, E. (2006). Responding to the coffee crisis: a pilot study of farmers' adaptations in Mexico, Guatemala and Honduras. *Geographical Journal,* 172(2): 156-171. Retrieved from: https://doi.org/10.1111/j.1475-4959.2006.00195.x
[181] Ha, D.T., & Shively, G. (2008). Coffee Boom, Coffee Bust and Smallholder Response in Vietnam's Central Highlands. *Review of Development Economics,* 12(2): 312-326. Retrieved from: https://doi-org.proxy.lib.duke.edu/10.1111/j.1467-9361.2007.00391.x

as a bonus commercial strategy[182]. Third are regional or country-level policy changes, which were outlined above. Ultimately, cost is determined by many factors, including how the crop is harvested and value-added processing before selling at gate. For example, wet processing has a higher payout than dry cherries, though it also involves more processing[183].

In recent years, C price and Robusta-price, the futures contract price for a shipping container of Arabica and Robusta coffee, respectively, has played an increasingly influential role in coffee production[184]. The Coffee "C contract" is the world benchmark for Arabica coffee and the Robusta Coffee Future is the world benchmark for Robusta coffee[185]. The underlying asset of the contract is the price of the physical delivery of exchange-grade green beans[186]. When the price drops, people will engage with the future contracts to secure lower prices later. In Colombia, the National Coffee Growers' Federation (FNC) purchases smallholder coffee based on the daily C price while other buyers offer prices at a certain amount or percentage above the FNC's price for parchment coffee. Additionally, since C and Robusta prices are calculated in USD, currency exchange rates also influence the price. Currently, the futures exchange puts a coffee future contract as the price for 17,000 kilos (37,500 pounds) of green coffee. This is more than what most small farmers' produce each year. It is the price due to economies of scale and not necessarily what a smallholder farmer would receive due to inability to reach scalability[187].

VII. Competing Crops and Land Use

Although individuals, families, and regional groups have direct effect on land use activities and land-use change, powers both close and far from home affect their decision-making process

The major themes surrounding coffee and land use include:

- Global factors, such as coffee prices and the demand for specialty, high-quality, or geographically unique coffee.
- Factors at the regional and family-scale, such as the profitability of alternative crops and the land use type of adjacent properties.

Landowners must also consider their local and regional context when deciding to convert or maintain forest cover. Kishor and Constantino (1993) focus on the economics of four primary land-use types to understand the incentives of land-use change. Aside from strict conservation, the private owner of quasi-forested land has a few options:

- Liquidation – harvesting commercial-grade timber as it becomes available, without any attempt to replant the land or maintain forest cover.
- Managed natural forest – harvesting mature timber but maintaining the same percent forest cover through time.
- Plantation – clear-cutting the land to create a timber monoculture.
- Cattle ranching – clear-cutting to make way for grazing.

A landowner's decision is further complicated by macrotrends, such as the price for alternative crops and niche products like certified 'green' timber. Kishor and Constantino (1993) found that at that point, regardless of the discount rate, sustainable management never wins from

[182] Eakin, H., Tucker, C. & Castellanos, E. (2006). Responding to the coffee crisis: a pilot study of farmers' adaptations in Mexico, Guatemala and Honduras. *Geographical Journal,* 172(2): 156-171. Retrieved from: https://doi.org/10.1111/j.1475-4959.2006.00195.x

[183] Luna, Fatima & Wilson, Paul. (2015). An Economic Exploration of Smallholder Value Chains: Coffee Transactions in Chiapas, Mexico. International Food and Agribusiness Management Association. 18.

[184] ICE. Coffee Futures (2021 Feb 20). *Coffee C ® Futures.* Retrieved from: https://www.theice.com/products/15/Coffee-C-Futures

[185] *Robusta Coffee Futures | ICE*. (n.d.). Retrieved April 21, 2021, from https://www.theice.com/products/37089079/Robusta-Coffee-Futures

[186] ICE. Coffee Futures (2021 Feb 20). *Coffee C ® Futures.* Retrieved from: https://www.theice.com/products/15/Coffee-C-Futures

[187] ICE. Coffee Futures (2021 Feb 20). *Coffee C ® Futures.* Retrieved from: https://www.theice.com/products/15/Coffee-C-Futures

an economic point of view[188]. This means that market signals alone are unlikely to make sustainable management a preferred option, though this is contested. However, if a landowner is considering the transition to coffee production, Ricketts et al. (2004) and Priess et al. (2007) advocate for a 0.25 ratio of forest cover to coffee production. The authors found that forest-based pollinators can measurably improve coffee yield and quality, which translates to an ecosystem service value of $60,000 over three years. Therefore, maintaining nearby forest provides a greater economic incentive than certain government subsidies, such as payments for ecosystem services (PES).

A final consideration is land sharing versus land sparing. Hulme et al. (2013) defines land sharing as wildlife friendly farmland, which cultivates a greater area to a lesser extent, and land sparing as intensively managed farmland, which cultivates a lesser area to a greater extent[189]. They found that biodiversity is higher when land sparing is employed because land sharing offers a poor substitute habitat. If individuals and organizations decide to cultivate coffee, they should be educated on the importance of maintaining or restoring forest cover. Farmers can use land sparing to maximize forest coverage and the associated economic benefit from ecosystem services, like natural pollination.

VIII. Migration and Urbanization

In Central America, farmers are reliant on migrant labor to complete the harvests. Costa Rica relies on workers from Nicaragua and Honduras relies on workers from Guatemala and Nicaragua[190]. A survey conducted by the United Nations in Tijuana, Mexico found that 28% of recent arrivals had worked in the agricultural sector. Similarly, Tucker et al 2010 reported that 28% and 27% of households in Mexico and Honduras had a household member who migrated in the prior five years which coincided with a coffee crisis[191].

In Vietnam, political reforms of the 1980s led to economic stability and subsequent urbanization. In 2008, almost half of Vietnam's population worked in agriculture. A decade later, this has drastically decreased as the service and industry sectors boom, now accounting for larger portions of Vietnam's GDP than agriculture. This is coupled with massive spending and investment in farming, which constituted the second highest expense for the country in 2019, which further incentivizes the migration of citizens out of rural areas[192]. It is projected that the urban population will be greater than the rural population by 2050, for the reasons outlined above, as well as the benefits of higher living standards[193].

IX. Impact & Recommendations

Soil Management -

---

[188] Kishor, N. M. & Constantino, L. F. (1993). Forest Management & Competing Land Uses: An Economic Analysis for Costa Rica. The World Bank: Latin American Technical Department – Environment Division.

[189] Hulme, M. F., et al. (2013). Conserving the Bids of Uganda's Banana-Coffee Arc: Land Sparing & Land Sharing Compared. PLoS ONE. 8 (2).

[190] Bloomberg. (2020, June 18). *Trouble brewing for high-end coffee growers amid Covid-19*. The Straits Times. https://www.straitstimes.com/business/economy/trouble-brewing-for-high-end-coffee-growers-amid-covid-19

[191] Tucker, C. M., Eakin, H., & Castellanos, E. J. (2010). Perceptions of risk and adaptation: Coffee producers, market shocks, and extreme weather in Central America and Mexico. *Global Environmental Change*, *20*(1), 23–32. https://doi.org/10.1016/j.gloenvcha.2009.07.006

[192] *Vietnam—Urbanization 2019*. (n.d.). Statista. Retrieved April 21, 2021, from https://www.statista.com/statistics/444882/urbanization-in-vietnam/

[193] *Vietnam: Urban population 2020*. (n.d.). Statista. Retrieved April 21, 2021, from https://www.statista.com/statistics/603397/vietnam-urban-population/

It is estimated that the harvest and removal of one ton of green coffee beans, removes 33, 1, and 30 kg of nitrogen, phosphorous, and potassium from the system, respectively[194]. These lost nutrients are returned to the field as highly soluble fertilizers, such as superphosphate, potassium chloride, and urea[195]. In reality, the constant use of fertilizers leads to changes in soil pH and excess nitrogen leaching and off-gassing as nitrate (NO3-) and nitrous oxide (N2O), respectively[196].

Zhao et al. (2018) found that electroconductivity (EC), phosphorous, iron, and zinc increased with continued monocropping. These parameters also negatively correlated with coffee plant dry weight in the lab and fresh coffee fruit yield in the field. A combination of intercropping and organic manure treatment can restore soil health and supplement lost nutrients. The recommendation is that on replanted land, remove the old trees and stumps, lime at a rate of 1.5 tons/ha, then solarize the soil for the next six months. In the second year and beyond, apply 5 kg of organic microbial fertilizer per hole per year, bury 30 kg of green manure per hole multiple times per year, and fertilize according to governmental guidelines[197].

Pest Management -

Studies show a positive correlation between root polyphenol concentration and natural nematode tolerance, indicating higher prevalence of these parasites on Robusta, as *C. canephora* has higher concentrations of polyphenols in its roots than *C. arabica*[198]. Recent studies have highlighted the ability of endophytic bacteria to reduce the presence and abundance of plant parasitic nematodes in coffee tree soil. This ability to reduce the population density of disastrous pests is a remarkable solution that may be scaled to dampen the negative impact of pest presence on coffee yield[199].

Irrigation Management -

Vietnam relies heavily on irrigation to optimize Robusta production, where it accounts for 15-20% of production cost[200].

Shade Management -

A farmer's choice for shade- or sun-grown coffee plots can create or destroy forests and biodiversity and influences the farming processes. In addition to removing forests and ecosystems, sun-grown plots need more care because there is less organic matter that naturally returns to the soil. A shade-grown coffee plot is more similar in composition to how wild coffee grows. While the surrounding ecosystem is managed to ensure the coffee's success, it is not entirely removed and thus ends up supporting the coffee growth[201].

---

[194] Pham, T., Nguyen, N. H., Yen, P. N. D., Lam, T. D., & Le, N. T. T. (2020). Proposed Techniques to Supplement the Loss in Nutrient Cycling for Replanted Coffee Plantations in Vietnam. Agronomy. **10** 905.

[195] Byrareddy, V., Kouadio, L., Mushtaq, S., & Stone, R. (2019). Sustainable Production of Robusta Coffee Under a Changing Climate: A 10-Year Monitoring of Fertilizer Management in Coffee Farms in Vietnam & Indonesia. Agronomy. **9** 499.

[196] Capa, D., Pérez-Esteban, J., & Masaguer, A. (2015). Unsustainability of Recommended Fertilization Rates for Coffee Monoculture Due to High N_2O Emissions. Agron. Sustain. Dev. **35** 1551 – 1559.

[197] Pham, T., Nguyen, N. H., Yen, P. N. D., Lam, T. D., & Le, N. T. T. (2020). Proposed Techniques to Supplement the Loss in Nutrient Cycling for Replanted Coffee Plantations in Vietnam. Agronomy. **10** 905.

[198] Trinh, P. Q., Wesemael, W. M. L., Tran, H. A., Nguyen, C. N., & Moens, M. (2012). Resistance Screening of *Coffea* spp. Accessions for *Pratylenchus coffeae* & *Radopholus arabocoffeae* in Vietnam. Euphytica. 185: 233 – 241.

[199] Hoang, H., Tran, L.H., Nguyen, T.H. *et al.* Occurrence of endophytic bacteria in Vietnamese Robusta coffee roots and their effects on plant parasitic nematodes. *Symbiosis* **80,** 75–84 (2020). https://doi.org/10.1007/s13199-019-00649-9

[200] Amarasinghe, U. A., Hoanh, C. T., D'haeze, D., & Hung, T. Q. (2015). Toward sustainable coffee production in Vietnam: More coffee with less water. *Agricultural Systems*, *136*, 96–105. https://doi.org/10.1016/j.agsy.2015.02.008

[201] *Sun-grown vs. shade-grown: How it impacts the environment and the farmers*. (n.d.). De La Gente. Retrieved March 11, 2021, from https://www.dlgcoffee.org/news/2017/4/6/coffee-cultivation-sun-grown-shade-grown-and-how-it-impacts-the-environment-and-the-farmers

X. Pest and Fungi impacts in Brazil

In Brazil, the primary coffee pest diseases and are coffee berry and leaf miner[202]. Coffee berry borer *(Hypothenemous hampei),* is one of the major insects of coffee that feed on coffee berries and this borer insect has an exponential population growth of 8.5% for every 1ºC temperature increase[203]. According to recent records, the coffee berry disease has surged in an area that grows approximately 40% of Brazil's crop, with estimated damage to Arabica coffee ranging from 5% to 30%. To quantify coffee berry borer (CBB) impact on coffee production, the percentage of yields effected based on historical data and predication was used, and thus assumed the worst scenario of coffee berry disease is 30% and best is 5% for Arabica cultivar. Unlike the coffee berry disease lacking strong evidence of a decline with technology improvements,

Coffee Leaf Miner (CLM) is responsible for the 30-70% losses of both Arabica and Robusta cultivars. Similar to coffee berry, the increased temperature allows two CLM rounds in producer regions, shortens the plague cycle, and finally stimulates high populations of adults and a large number of eggs in leaves. Brazil can average eight generations per year, sometimes reaching as high as twelve[204]. To quantify coffee leaf miner the pests' impacts on coffee production, the percentage of yields effected based on historical data and predication was used. Due to a decreased of up to 50% when plants are fertilized with organic material, a 35% decrease in yield was used as the worst scenario for leaf miner, and 15% decrease in yield as the best scenario[205].

The primary fungi-related coffee disease is coffee leaf rust (CLR), caused by *Hemileia vastarix*[206]. The Gompertz growth model best describes CLR outbreaks. The main climate variables for predicting CLR's infection rate are monthly minimum air temperatures and relative humidity. Today, coffee leaf rust (CLR) is widespread in Brazil, and it continues to cause yield losses of 30 to 50 %[207]. The 30% and 50% losses in yield production were adopted as the worst and the best scenario accordingly.

XI. Covid-19

Unsurprisingly, the pandemic has brought about a new set of challenges for coffee farmers. They can't find enough help during harvests due to a combination of policies intended to curb the spread of Covid-19 by limiting migration, insufficient and expensive testing, and general fears of the virus. Most farmers are reliant on migrant harvesters for cheap labor, but as new border policies require negative tests prior to entry, extra hands are either delayed entering or unable to enter at all. Farmers have had to look to in-country harvesters who may be more

---

[202] Ghini, R., Hamada, E., Pedro, J., Mário, J., Marengo, J. A., & Gonçalves, R. R.V. (2008). Risk analysis of climate change on coffee nematodes and leaf miner in Brazil. *Pesquisa Agropecuária Brasileira*, *43*(2), 187-194. https://doi.org/10.1590/S0100-204X2008000200005

[203] Jaramillo, J., Chabi-Olaye, A., Kamonjo, C., et al. (2009). Thermal Tolerance of the Coffee Berry Borer *Hypothenemus hampei*: Predictions of Climate Change Impact on a Tropical Insect Pest. *PLoS ONE,* 4(8): e6487. Retrieved from: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0006487#:~:text=Based%20on%20the%20non%2Dlinear,3).

[204] Dantas, J.,Motta, I., Vidal, L., Bílio, J., Pupe, J.M., Veiga, A., Carvalho, C.H.S., Lopes, R.B., Rocha, T.L., Silva, L.P., Pujol-Luz, J.R., & Albuquerque, É.V. (2020 Oct 30). A Comprehensive Review of the Coffee Leaf Miner Leucoptera Coffeella (Lepidoptera: Lyonetiidae), With Special Regard to Neotropical Impacts, Pest Management and Control. *Preprints*. Retrieved from: https://www.preprints.org/manuscript/202010.0629/v1

[205] Sabino, P.H. de S., Junior, F.A.R., Carvalho, G.A., & Mantovani, J.R. (2018). Nitrogen Fertilizers and Occurrence of Leucoptera coffeella (Guérin-Mèneville & Perrottet) in Transplanted Coffee Seedlings. Coffee Science, 13(3): 410–414. Retrieved from: http://www.coffeescience.ufla.br/index.php/Coffeescience/article/view/1458/PDF1458

[206] Ghini, R., Hamada, E., Pedro, J., Mário, J., Marengo, J. A., & Gonçalves, R. R.V. (2008). Risk analysis of climate change on coffee nematodes and leaf miner in Brazil. *Pesquisa Agropecuária Brasileira*, *43*(2), 187-194. https://doi.org/10.1590/S0100-204X2008000200005

[207] Zambolim, L. (2016). Current status and management of coffee leaf rust in Brazil. *Tropical Plant Pathology,* **41:** 1–8 (2016). Retrieved from: https://doi.org/10.1007/s40858-016-0065-9

expensive or newer to the job and thus less efficient. Coffee needs to be picked quickly before the rains come and ruin the crop and the pandemic has completely disrupted the ability of farmers to do this as they normally would[208]. One example is Honduras where coffee exports fell 18% in January 2021[209]. Even if a farmer is able to harvest all of their coffee, there are problems down the value chain. Many countries have decreased non-essential imports to slow the number of workers in the port at the same time. This has only led to paranoia over whether there will continue to be enough supply to meet demand and markets are seeing larger roasters buying as much coffee as possible now to hedge against a drop in supply down the road[210]. Demand has also changed, with at-home consumption and specialty coffee shops increasing. This has particularly hurt farmers growing specialty coffee because the demand for fancy lattes at a coffee shop is down in many Western countries. The mix of Arabica and Robusta has changed. Coffee from home is more likely to contain a higher percentage of Robusta while coffee from specialty shops will be a higher percentage Arabica[211].

---

[208] *Coronavirus puts Honduras' coffee harvest in jeopardy*. (2020, December 31). AP NEWS. https://apnews.com/article/tegucigalpa-honduras-coronavirus-pandemic-latin-america-7553ffdd5f461e9257c39c41a3e2e5c3

[209] *Honduran coffee exports fall 18% in January as pandemic hits demand | Reuters*. (n.d.). Retrieved March 11, 2021, from https://www.reuters.com/article/honduras-coffee-idUSL4N2K80K5

[210] Kapur, K. (2020, April 17). *Impact of COVID-19 on Africa's Cacao and Coffee Producers*. Medium. https://medium.com/moka-origins/impact-of-covid-19-on-africas-cacao-and-coffee-producers-8909761d7730

[211] *Trouble brewing for high-end coffee growers amid Covid-19, Economy News & Top Stories—The Straits Times*. (n.d.). Retrieved March 11, 2021, from https://www.straitstimes.com/business/economy/trouble-brewing-for-high-end-coffee-growers-amid-covid-19