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Coffee Supply Chain Planning under Climate Change

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I am submitting herewith a thesis written by Rui Zhou entitled "Coffee Supply Chain Planning under Climate Change." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

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Coffee Supply Chain Planning under Climate Change

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Rui Zhou

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Abstract

Coffee is a valuable crop for many tropical countries and provides an export value estimated at US$30.1 billion in 2019 worldwide. Coffee trees are climate sensitive. Published studies show that climate change is projected to have a negative impact on suitable growing areas for coffee beans, so the coffee bean production is facing a rising risk. At the same time, the consumption of coffee is increasing in recent years, especially in Asian countries. Therefore, the sustainability of the coffee industry has become a concern shared by all participants along the coffee supply chains. Decision making in arabica coffee bean cultivation, which includes long-term shade management and short-term annual management practices (e.g., fertilization management and irrigation management), and logistics is focused in this study on a global scale. Two-stage stochastic programming is adopted to minimize the total cost, including cultivation cost, roasting cost, shortage cost, and logistics cost under different climate scenarios.

A case study for a global coffee beverage company is presented with data collected from both practice and literature. The arabica coffee species distribution model by citation (Ovalle-Rivera et al., 2015) shows that the suitable harvesting area will decrease due to climate change in most of the coffee growing countries by 2050. This study tries to answer the questions of whether arabica coffee yield will meet the consumption demand in the future. To increase the arabica coffee yield, medium-level shade management is a possible long-term strategy while management practices may be changed based on weather. To have a substantiable coffee supply chain, the global coffee beverage companies have programs to help coffee farmers through technical assistance and financial support. In addition, local governments may also provide support to farmers, such as educational programs, working condition improvement, and medical service.

Keywords: coffee supply chain, climate change, agriculture management practices, optimization, two-stage stochastic programming, sustainability

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1 Introduction

Coffee is one of the most popular beverages around the world. According to the Coffee Market reports from the International Coffee Organization (ICO, 2020), the growth of coffee consumption in Asia, Oceania and Africa is outpacing other regions and leads to the increase of the global demand in coffee bean every year. However, world coffee bean exports have decreased by 5.8% in 2019/2020, and world coffee production decreased by 0.9%, especially the decline by 3.2% in South American. Arabica coffee, which accounts for 70% global coffee production, could decrease by 50% or more by 2088 under all available future projections based on multiple general circulation models (GCMs), emission scenarios and migration scenarios (Moat et al., 2019). The International Union for Conservation of Nature found that 60% of all coffee species are facing a high risk of extinction, threatened by climate change and deforestation, and many original protected areas would not be suitable for coffee trees growing in the future (Rodríguez, 2019).

Arabica coffee has been proven highly sensitive to climate change. The optimal growing temperature is 18~24 °C, and precipitation is 1,200-2,200 mm per year. The variability of climate has been the main factor for the yield decline of arabica coffee beans in many coffee growing regions (Davis et al., 2012; Jassogne et al., 2013; Bunn et al., 2015; Craparo et al., 2015; Bunn et al., 2018). Data-driven research indicates that there is a 137 ± 16.78 kg/ha annual yield decline with every 1℃ rise in minimal temperature, and the average production will drop to 145 ± 41 kg/ha by 2060 (Craparo, 2015). Lots of plantations are suffering from vulnerable yield, especially small farms in the developing countries. Preserving coffee species should not be burned by farmers alone, the entire coffee community should contribute.

Sustainable coffee bean production has been discussed by academia, governments, international coffee organizations, and private sectors. International Coffee Agreement 2007 pointed out that sustainability regulation on the coffee industry should focus on environmental governance, economic, and social terms (ICO, 2007). Farmers, government agents, and global coffee companies share a collective enthusiasm for the coffee bean sustainability (Arifin, 2010). Majority of coffee plantations are owned by smallholders, who lack of technologies and capital. Fortunately, to enhance sustainability, some global coffee beverage companies like Starbucks is taking farmer's interest into account and starting to provide them financial and technical support (Starbucks, 2020).

Coffee farming systems can not only help to increase the yield of coffee beans but also improve farmers' livelihoods and local biodiversity. One of the most essential and traditional cultivation systems of coffee growing is shade tree management shown in Figure 1-1.

Figure 1-1 (A) Full Sun Plantation. (B) Shade Plantation

*Source: (How Coffee Is Made – 15 Steps From Seed To Cup; Coffee bushes in a shade-grown organic coffee plantation on the Stock Photo: 66288543 - Alamy)

Native trees are used to provide natural nutrition and suitable canopy for coffee trees. The recommended shade level varies with the altitudes, soil topography, climate, and available labor of the coffee plantations (Souza, 2000). Although some research shows that from the 1990s and the 2010s, coffee harvesting under the shade system was decreasing in lots of coffee growing regions such as Colombia, Brazil, and Mexico, the shade system is still an economical and potentially effective strategy to help farmers in the areas where the crop plants might face extremes climate (Lin, 2007). Diversified shade systems are needed for the sustainability of coffee landscapes and are able to promote greater resilience to global markets and climate changes (Jha et al., 2014).

The application of fertilization is also crucial for coffee productivity, whose effectiveness depends on various factors, including the type of production system, coffee variety, age of coffee trees, and soil fertility status (Melke et al., 2014). Nitrogen (N) demand is the highest among all types of soil nutrients, and N absorption is fundamental for plant growth that can influence coffee bean yield. Ideal N fertilizer use can reduce production cost and environmental impact while increasing the production of coffee beans (Bruno et al., 2011).

Decreased precipitation and more evapotranspiration demand more irrigation due to air temperature rise (Fares et al., 2016). The adoption of irrigation also has a positive effect on plant height, crown diameter and stalk diameter for the long-term performance of coffee trees. What's more, irrigation provides a more controlled production environment and avoids the production loss due to soil water deficits for coffee trees. Coffee yield is higher with irrigation than non-irrigated treatment since irrigated treatment has greater root concentrations. The average yield of irrigated coffee is 2,623 kg/ha, while the number without irrigation is 1,026 kg/ha. (Sakai et al., 2015).

While promising, we notice that most research focuses on either how climate change affects coffee species distribution or the relationship between coffee yield and different agriculture systems. Considering sustainable coffee industry development needs support from farmers, governments, international organizations, private coffee companies and even customers but missing in the literature is critical to a systematic understanding on the interactions among all participators the balance of all the needs. To address this research gap, we develop a two-stage stochastic model to study the optimal coffee supply chain planning under different climate scenarios considering both farmers' and coffee beverage companies' costs and give some policy recommendations in sustainable coffee development for every participator.

This study is organized as follows: Section 2 reviews the previous studies related to the climate change impact on coffee, sustainable management in the coffee industry, and three sustainable supply chain modeling approaches. In Section 3, we propose a two-stage stochastic formulation of the coffee supply chain planning problem under various climate scenarios. In Section 4 and Section 5, we use a real-world case to present the experimental results. First, we predict future arabica coffee production under different climate scenarios in those arabica coffee beans supply countries. Second, assessing the effectiveness of different shade management levels and yearly fertilization and irrigation input planning, and getting the optimal global coffee bean logistics. Section 6 discusses the implication of this study on policies for farmers, coffee beverage companies and government agents, then discuss future work. Finally, Section 7 concludes this thesis.

2 Literature Review

2.1 Climate Change Studies of Coffee Production

The effects of the variability of climate factors, such as air temperature, solar radiation, relative humidity, and rainfall on arabica coffee already shown in some regions. Climate change could lead to the establishment of a coffee plantation to new areas and may have conflicts with other natural forests, with have negative implications for biodiversity and ecosystem.

The suitable arabica coffee cultivation areas will lose 56% (±7%) by 2050 (especially in Brazil, East Africa, and Madagascar) while the future suitable regions of robust coffee will extend more than double, and the major suitable areas will locate in forested locations. In Brazil, higher temperatures and dry conditions during growing seasons may harm coffee production and quality and cause a sharp decrease in production and suitable areas. In extrema cases, the temperatures can reach 40 ℃ occurs on sunny days in unshaded crops. The coffee yield during 2011-2100 under two greenhouse concentration scenarios: RCP4.5 and RCP8.5 will decrease 25% by the end of the twenty-first century, and the areas fully adequate will move to higher altitude regions. In Haiti, climate changed also has a negative impact on coffee production in the short-mid & long-term. The suitable climate area for both production and spatial statistics using Geographical Information System (GIS) shows that the change in temperature and precipitation will lead to coffee lose suitability in lower altitudes. In Kenya, the optimal altitude for arabica coffee will increase 200 m.a.s.l by 2050 due to increasing temperature. In Colombia, to maintain coffee yield, arabica plantations would have to be moved by 167 m in altitude for every 1 ℃ increase of temperature. (Camargo, 2010b; Eitzinger et al., 2013; GIZ, 2011; Magrach et al., 2015; Tavares et al., 2018)

Climate change and variability also increase the risk of coffee pests and diseases, which can reduce coffee yield and quality and increase production cost. For smallholder coffee plantations in Africa, Asia, and Latin America, the effect of coffee berry disease and coffee leaf rust would be worse since they lack alternative economic options. In Zimbabwe, some species distribution modeling approaches like Boosted Regression Trees and Generalized Linear Models show that the precipitation related variables are the most critical factors of the distribution of coffee white stem borer. In East Africa, using the CLIMEX model to forecast the future distribution of *H.hample*, the coffee berry borer, under different scenarios (A2A and B2B for the HADCM3 model) and the result shows that the situation is worsening and the number of *H.hample* generations increases every year (Jaramillo et al., 2011; Kutywayo et al., 2013; Mafusire et al., 2010).

2.2 Sustainable Supply Chain Management in the Coffee Industry

Sustainable supply chain management is the management of information, finance, and material among the supply chain processing that meets the needs of present economically, environmentally, and socially friendly (Seuring et al., 2008). The food industry is a very dynamic industry with highly changeable customer demands, and the production origin, inputs, and labor are becoming more concerned, which connects every member among the food supply chain to collaborate to come up with more adaptation strategies (Beske et al., 2014). Sustainability helps stakeholders in the coffee supply chain network to have cost-effective and environmentally-friendly harvesting, appreciate farmers' rights, and offer higher quality coffee products for customers (Wahyudi et al., 2012). Sustainable Coffee Challenge Organization establishes a sustainability framework that consists of farmers' livelihoods, nature conservation, supply sustainability, and market demand strengthening (Sustainable Coffee Challenge). To sum up, three aspects: farming system prevalence, environmental management, and social responsibilities focused on sustainable coffee supply chain network as follows:

About farming system prevalence, implementing different farming systems associated with shade management and management practices such as fertilization and irrigation are important methods for crop harvesting and has been concerned a lot in academia. Comparing the benefits of exotic versus native shade trees on coffee production and evaluate the relevance of shade trees and management practices on it, and the result indicates that vast diversity and density of flora can decrease production, while irrigation can increase production by 16% (Boreux et al., 2016). The primary biochemical composition of fertilizer includes nitrogen, photophores, potassium fertilizer, and the fertilization types are organic and inorganic (Verhage et al., 2017; VINECKY et al., 2017). Most of the research focuses on the interaction of different levels of shade with different levels of fertilization and irrigation management on coffee production, flavor, and quality. In small-scale Peruvian coffee systems, medium-shade plantations have higher gross revenues and coffee yields. There are no differences between net income and benefit-cost ratio with different shade management but lower with higher input practices. In the dry and hot region of southwest China, the irrigation amount of 80% full irrigation and high N input had higher arabica coffee yield and quality (Jezeer et al., 2018a; Liu et al., 2016).

Environmental management has also played an essential role in reducing negative climate change impact, including water conservation, forest conservation, and restoration. First, water plays a crucial role in the growth and development of coffee trees. As a result of water risk due to climate change, water management becomes more critical. It is increasingly difficult for coffee farmers to get enough water due to the environmental degradation, climate change, and inappropriate water resources use. Therefore, building more water instruments is crucial to deal with those issues. The utilization of chemical input will cause water pollution. Native tree species are the most effective for protecting water resources (Cerdán et al., 2012; Quiroga et al., 2015).

Second, although coffee yield might decrease under the high-density shade, native forest trees can protect coffee trees, habitat for animals, and additional income for farmers. By restoring forests, the coffee industry can grow benefits now and future, for both farmers and the planet. Large basal diameters and a high number of secondary orthotropic shoots have a higher yield. Comparing with traditional coffee cultivation, which is associated with low tree species diversity and simple forest structure, climax species, and suitable trees should be planted with longer-living climax species to maintain coffee productivity, and they are essential for the preservation of forest cover and biodiversity (Aerts et al., 2011).

In the social responsibility's aspect, livelihoods improvement, fair-trade certified coffee, and sustainability in coffee consumption are concerned a lot. The livelihoods of smallholder farmers had been affected a lot due to extreme weather events. Bielecki et al. (2019) present a qualitative study of smallholder farmers' decision process who are struggling with the negative effect on coffee production due to climate change. They come up with a livelihood's framework including three stages, and the first stage is analyzing the producers' context (e.g., history, politics, *etc*.), resources, institutions, and organizations, the second stage is analyzing the vulnerabilities in context, the third stage is analyzing the response to vulnerabilities. Harvey et al. (2018) survey 860 smallholder farmers in six Central American nations and find out that they are hindered by the lack of information on how to respond to climate change, even though they have observed the rising temperature, changeable precipitation, and some other extreme weather. Helps in climate adaptation policies and programs form governments and practitioners are very needed.

Fairtrade is made to improve products' values from small-scale producers in developing countries. There are a minimum price and a social premium to buy the fair-trade certified products, and buyers also have a long-term contract with producers. Comparing many effects on production, sales and participation of fair-trade organic coffee vs. non-Fair-trade and conventional coffee, the long-term fair-trade certified coffee has a positive effect on the coffee price, trade volumes, and higher entrepreneurial capacity (Dragusanu et al., 2014; Elder et al. , 2012; Ruben et al. 2012).

Members in the coffee supply chain are not only caring about the origins of coffee beans, but they are also making an effort in the sustainability of coffee consumption. Starbucks is planning to build 10,000 green retail stores by 2025, recycle coffee cups by 2022, and operate 100% renewable energy by 2020. They also create opportunities for everyone in the communities they serve. They are also customizing benefits for their partners worldwide, providing college education through the Starbucks College Achievement Plan, hiring veterans and military, and providing jobs for youth between 16-24 who are disconnected from school and work (Starbucks Report).

2.3 Sustainable Supply Chain Modeling Approaches

Sustainable supply chain management has caught up much attention in both the academic and corporate field in recent years. It makes companies cooperate responsibility to achieve higher efficiency in logistics performance and resource usage with condensing the three dimensions of sustainability: economic, social, and environmental goals. The incentives of SSCM includes legal demands, customer demands, response to stakeholders, competitive advantages, environmental and social pressure, and reputation loss. Five methodologies are applied: theoretical and conceptual papers, case studies, surveys, modeling, and literature review. In SSCM, social impacts usually are evaluated before they are integrated into modeling approaches because they are hard to evaluate. Life-cycle assessment-based models mainly consider environmental dimensions. Economic dimensions are related to cost and revenue dominate, and some of the analytical hierarchy process papers are talking about this (Beske et al., 2014; Seuring, 2013; Seuring et al., 2008). The framework of sustainable supply chain modeling approaches is showing as follows:

Life cycle assessment refers to “compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle” (International Organization for Standardization, 2006). In the last decade, LCA was concerned about a different level of products, sectors, and economies. For the next stage, a life-cycle assessment will develop from traditional environmental LCA to a more comprehensive life-cycle sustainability assessment (people, planet, and prosperity) within recent years. LCA-based models usually assess environmental impacts along a supply chain and minimize them and form a background with other research approaches, providing the product optimization perspective on a general supply chain wide aspects (Simonen, 2014). The life cycle of coffee includes cultivation, milling, and roasting. Nowadays, people are researching carbon dioxide footprint, energy potential, and waste in coffee LCA. More details will be discussed in the next section.

The Equilibrium model is a standard modeling technique to balance environmental and economic factors and find an equilibrium or optimal solution, which simultaneously study three decision-makers: manufacturers, retailers, and consumers. Nonlinear complementarity problems formulations, and smoothing Newton algorithms are applied as solution methods for solving these models (Hosseini et al., 2019). The lean and green supply chain methods are applied to evaluate the performance of a supply chain from both managerial and environmental viewpoints, which build on three aspects: LCA, supply chain return on assets, and customer satisfaction. Using thermodynamic input-output analysis to determine the reliance of industrial networks in natural and economic capitals helps industrial sustainability metrics restructuring. The supply chain models with numerous decision-makers and associated with environmental concerns can be formulated, analyzed and solved qualitatively by using a time adjustment process disequilibrium dynamics model (Kainuma et al., 2006; Nagurney et al., 2003; Ukidwe et al., 2005)

Multi-criteria decision-making methods focus on trade-off among conflicting objectives based on societal decisions compared with the equilibrium situation. The analytic network process, decision-making trial, and evaluation laboratory technique were combined as a hybrid multi-criteria decision-making model for international trade practices. Multi-criteria decision analysis techniques and spatial analysis were combined to assess soil contamination risk and vulnerability. The vulnerability assessment results support the regional risk assessment at a regional scale for the ranking of potentially contaminated sites (Wang, 2012; Zabeo et al., 2011).

3 Coffee Supply Chain Planning with Uncertainties

3.1 Problem Description

There are two main parts of the coffee bean supply chain: cultivation and logistics. First, farmers play the most important role in cultivation, and they will be involved in every step of the coffee growing and processing. During the harvesting seasons, they will pluck the coffee cherries by hands from coffee trees and then process them to green coffee beans for selling. Global coffee beverage companies will buy those green coffee beans from the local farms directly or some other big secondary coffee cooperatives. After that, green coffee beans are exported to consumer countries oversea for roasting in the roasting centers, and then roasted coffee beans will be sent to retailer stores. Global coffee beverage companies usually handle logistics. Figure 3-1 illustrates the coffee bean supply chain.

3.2 Variables Definition for Supply Chain

A stochastic program combing cultivation and logistics are proposed in this section. The goal is to find the best shade management, management practices and logistics network under different climate scenarios, with the minimum total cost for farmers and coffee companies. The two-stage stochastic programming is introduced first for a farming arrangement under climate and demand uncertainties. After that, we can describe the logistics flows, a set of sources and their supplies, a set of destination and their demand, and the variable cost of labor and fertilizer input associated with each source-destination pair.

The model considers N coffee bean source countries (*j* as its index) during *T* years (*t* as its index). The coffee bean cultivation area in country *j* is A_j, which is assumed to remain constant. Farmers in each country have $E = 4$ shade management options (*e* as its index), full sun, low shade, medium shade and high shade. Therefore, in the first stage, farmers decide σ percentage area that

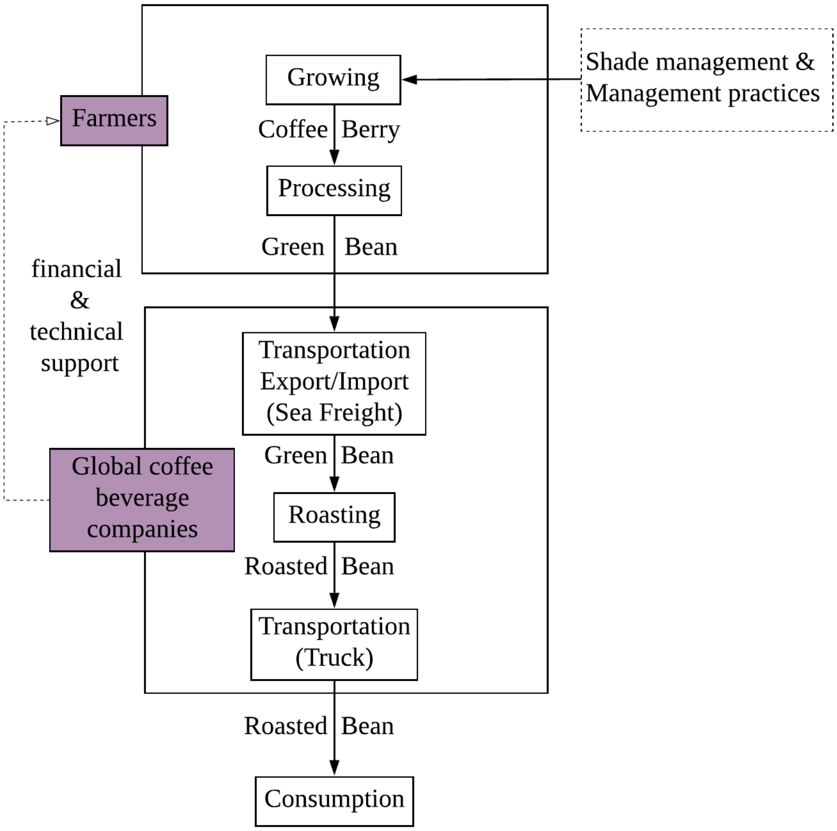


Figure 3-1 Coffee Bean Supply Chain

uses shade management e that is adopted in source country j, σ_{je}. The shade management are long-term decisions due to its large financial and time investment so that made at the beginning of the planning horizon. In each year, farmers also make fertilization management decisions. The management practices decisions could be adjusted based on weather conditions such as temperature and precipitation in this growing region. Consider S set of climate scenarios s, $s \in S$. Using p^s to represent the probability of climate scenario s. This study considers $Q = 4$ management practices options (q as its index), no fertilization and no irrigation, no fertilization but irrigation, fertilization but no irrigation, both fertilization and irrigation. Therefore, in the second stage, farmers decide θ percentage area that uses fertilization management q in country *j* in year *t* under climate scenario s, θ_{jtq}^{s}.

Yield is a key parameter in the optimization model and must be calculated prior to solve the optimization problem. The yield of each country *j* in year *t* under climate scenario *s*, applying shade management e and management practices q, is considered to be the sum of two parts: the base yield, Y_{jte}^{s}, which is only affected by the shade management, and the additional yield, B_{jtq}^{s}, which is the marginal effect of management practices and the effect between shade, fertilization, and irrigation. . The base yield (kg/ha) obtained in coffee beans source country *j* depends on the decisions on shade management *e*, which is the yield per hectare multiplied by suitable growing areas and a ratio. Using the projections of climate models, we can calculate the time series of future yield per hectare under the assumption of historical levels of coffee growing seasons monthly average temperature and precipitation using the regression relationship (de Oliveira Aparecidolim et al., 2017). To simplify the decision problem, the time series of future yield per hectare is further converted to time series of yield, using an appropriate threshold (e.g., historical average yield in the country). The joint probability distribution of future yield per hectare is unknown. However, different climate model simulations sample the joint probability distribution of the time series of future temperature, precipitation translates into samples from the joint probability distribution of future base yields. The future suitable growing areas can be obtained using a species distribution model. Additional parameter uncertainty can be considered in the impact of fertilizer and irrigation inputs on yield. Fertilizer and irrigation inputs are modeled as recourse options that can be used to further increase future yields to meet the coffee demand. The additional yield (kg/ha) that can be obtained in coffee beans source country *j* depends on the decisions on management practices q. Later, we will talk about the cost of cultivation.

As we discussed, the cost of coffee bean cultivation involves two parts. The first part involves the one-time fixed cost ($/ha) associated with investing in coffee shade management. F_e denotes the unit fixed cost ($/ha/y) by using shade management e. The second part involves the annual horizon variable cost of labor and associated with implementing fertilizer and irrigation input. G_q denotes the unit variable cost ($/ha/y) by using management practices q. Overall the cultivation involves making two stages decisions based on scenarios of the future yield of coffee beans and the cost of different options as discussed above. After cultivation, green coffee beans will be shipped to the consumer countries. Next, we will talk about logistics.

3.3 Two-Stage Stochastic Model

The following paragraphs are focusing on the logistics of coffee beans from source countries to retailer stores in consumer countries. The logistics involves three processing flows. Demands need to be fulfilled all the time, and inventory is not considered. First, an annual percentage I_j of coffee beans produced in coffee beans source country j is exported to the consumer countries. P_j is the percentage of the arabica coffee beans in coffee beans source country j exported to the United States. I_j and P_j is assumed to be a fixed number for each country j every year. The product of I_j and P_j represented by V_j is the final percentage of arabica coffee beans exported from each country j to the U.S. Green coffee beans are shipped to port l ($l \in \{1, \dots L\}$, L is the total numbers of the ports) by ocean shipping. Second, the green coffee beans are sent to roasting center r ($r \in \{1, \dots R\}$, R is the total numbers of the roasting centers) from port l by trucks. The roasting capacity of each roasting center r in year t is C_{rt}. The unit roasting cost of roasting centers r is Q_r. Third, the roasted coffee beans are sent to state m ($m \in \{1, \dots M\}$) in the U.S. by trucks. The number of kilogram roasted coffee beans consumed in state m in year t is D_{mt}.

The logistics cost is the unit transportation cost multiplied by transported coffee bean volume, which is calculated as follows for all of the processing flows.

1. The cost of shipping from source country *j* at port *l* in the destination countries is $W_{jl} \times h_{jlt}^{s}$ (\$), where h_{jlt}^{s} (kg) is the coffee beans import from source country *j* at port *l* in year *t* under climate scenario s, and W_{jl} (\$/kg) is the unit ocean shipping cost from source country *j* to port *l*.
2. The cost of shipping from port *l* to roasting center *r* is $J_{lr} \times u_{lrt}^{s}$ (\$), where u_{lrt}^{s} (kg) is the coffee beans transported form port *l* to roasting center *r* in year *t* under climate scenario s, J_{lr} (\$/kg) is the unit truck transportation cost from port *l* to roasting plant *r*. The unit roasting cost in roasting center *r* is Q_r. The total cost of roasting in roasting center *r* in year *t* under climate scenario *s* is H_{rt}^{s} (\$).
3. The cost of shipping from the roasting center *r* to state m is $K_{rm} \times x_{rmt}^{s}$ (\$), where x_{rmt}^{s} (kg) is the roasted coffee beans shipped from roasting center *r* to retail stores in state m in year *t* under climate scenario s, K_{rm} (\$/kg) is the unit truck transportation cost from roasting center *r* to state m.

Transportation loss is also associated with each processing flow. Before ocean shipping, the loss in the coffee beans is the sum of the annual processing loss in coffee beans in coffee beans source country *j* and the annual storage loss in source country *j*. During ocean shipping, there is an annual coffee bean loss (%) from source country *j* to the ports, and Z (%) coffee bean will be left after subtracting the total loss before roasting. After arriving in the U.S., Υ (%) roasted coffee beans will be left after subtracting the loss during roasting process in roasting centers.

When the arabica coffee bean supply cannot meet the demand, the coffee beverage company will have shortage O_{mt}^{s} (kg) in state m in year *t* under climate scenario *s*. P (\$/kg) is the profit rate, in this study we use a big number in the calculation. The shortage cost will also be considered in the objective function.

The overall objective function combines the total cost of both farmers and coffee companies can be represented as follow:

$$\text{Min} \sum_{j=1}^{N}\sum_{e=1}^{E} F_e \sigma_{je} A_j + p^s \sum_{t=1}^{T}\sum_{s=1}^{S}\Big(\sum_{j=1}^{N}\sum_{q=1}^{Q} G_q \theta_{jtq}^s A_j + \sum_{j=1}^{N}\sum_{l=1}^{L} h_{jlt}^s W_{jl} + \sum_{l=1}^{L}\sum_{r=1}^{R} u_{lrt}^s J_{lr} + \sum_{r=1}^{R}\sum_{m=1}^{M} x_{rmt}^s K_{rm} + H_{rt}^s + P\sum_{m=1}^{M} O_{mt}^s\Big) \tag{1}$$

s.t.

$$Z \cdot V_j\Big(\sum_{e=1}^{E} Y_{jte}^s \sigma_{je} + \sum_{q=1}^{Q} B_{jtq}^s \theta_{jtq}^s\Big) \geq \sum_{l=1}^{L} h_{jlt}^s \qquad \forall s, \forall t, \forall j \tag{2}$$

$$\sum_{j=1}^{N} h_{jlt}^s \geq \sum_{r=1}^{R} u_{lrt}^s \qquad \forall s, \forall t, \forall l \tag{3}$$

$$\Upsilon \cdot \sum_{l=1}^{L} u_{tlr}^s \geq \sum_{m=1}^{M} x_{rmt}^s \qquad \forall s, \forall t, \forall r \tag{4}$$

$$\sum_{l=1}^{L} u_{lrt}^s \leq C_{rt} \qquad \forall s, \forall t, \forall r \tag{5}$$

$$\sum_{r=1}^{R} x_{rmt}^s + O_{mt}^s \geq D_{mt} \qquad \forall s, \forall t, \forall m \tag{6}$$

$$Q_r \cdot \sum_{l=1}^{L} u_{lrt}^s = H_{rt}^s \qquad \forall s, \forall t, \forall r \tag{7}$$

$$\sum_{e=1}^{E} \sigma_{je} = 1 \qquad \forall j \tag{8}$$

$$\sum_{q=1}^{Q} \theta_{jtq}^s = 1 \qquad \forall s, \forall t, \forall j \tag{9}$$

$$\sigma_{je}, \theta_{jtq}^s, h_{jlt}^s, u_{lrt}^s, q_{rt}^s, x_{rmt}^s \geq 0 \tag{10}$$

The overall objective function (1) minimizes the total cost. One part is the objective of the two-stage stochastic programming model, which is to minimize the total cultivation cost. The total cultivation cost includes the fixed cost at the first stage by using different coffee shade management, which is $F_e \times \sigma_{je} \times A_j$, and the variable cost by using different fertilizer levels at the second stage, which is $G_q \times \theta_{jtq}^s \times A_j$. Another part is the total transportation cost $h_{jlt}^s W_{jl} +$

$u_{lrt}^{s} J_{lr} + u_{lrt}^{s} J_{lr}$, the total roasting cost of roasting centers, which is H_{rt}, and the shortage cost $P \times O_{mt}^{s}$.

Constraint set (2) makes sure that, the sum of base yield and additional yield, multiplied by left percentage with processing loss and the annual percentage of coffee beans exported in all source country, should greater than or equal to the import demand of coffee companies in that source country under climate scenario s. Constraints (3)-(6) are among the standard constraints in the logistics model. Constraint (3) makes sure that coffee beans imported from source countries at the U.S. ports under different climate scenario *s* must be great than or equal to the coffee beans transported from ports to roasting centers. Roasted coffee beans transported from ports to roasting centers must be equal to the roasted coffee beans shipped from the roasting center to retail stores under climate scenario *s*, restricted by constraint (4). Constraint (5) is used to guarantee the roasted coffee beans at the roasting centers do not exceed the capacity of roasting centers. Constraint (6) makes sure that the roasted coffee beans shipped from the roasting centers to retail stores at states add shortage to meet the consumer demand. Constraint (7) guarantees the total roasting cost equals unit roasting cost times the roasted coffee beans shipped from roasting center *r* to retail stores in state *m* in year *t* under climate scenario s. Constraint set (8) and (9) make sure that the total area that uses coffee shade management e, and the total area that uses management practice q should be equal to 100% in the same country.

4 Data and Parameters Setting

4.1 Global Coffee Bean Supply Chain

In this section, the proposed two-stage stochastic program is applied to Starbucks, which occupies around 40% of the coffee industry business in the U.S. (Statista, 2020), as a case for global coffee supply chain. Starbucks is one of the most successful and popular coffee companies around the world. In the United States, Starbucks operates 15,149 coffee shops as March 2020. The goal is to evaluate the future decision making of technical support, financial investment and logistics under different climate scenarios for Starbucks. Please note that this study was not a collaboration with Starbucks and all data about the company were obtained from publishing available sources.

Starbucks imports coffee beans mainly from Colombia, Brazil, Honduras, Peru and Ethiopia. Coffee beans imported through the New Orleans, and Savannah ports are bulk commodities, while Coffee beans imported through the New York, Oakland, Virginia, Portland, Seattle, Everglades, Jacksonville, and Houston ports are containerized (Taylor, 2013). Green coffee beans are then be transported to Starbucks' five roasting centers (Kent, WA; Minden, NV; York, PA; Gaston, SC; and Augusta, GA). After roasting, roasted coffee beans are delivered to different states around the U.S. Our study only considers the 48 continental states and Washington D.C. because Alaska and Hawaii are far away from other states and have different transportation routes. The abstract illustration of the coffee supply chain map for Starbucks is illustrated in Figure 4-1.

Figure 4-1 Top 5 Coffee Bean Exporting Countries for Starbucks

4.2 Data Sources

Table 4-1 lists the sources of all needed parameters for the optimization model. Agriculture data like current arabica coffee harvesting areas, annul export of arabica coffee bean volume, annul exported arabica coffee bean to the United States are obtained from the U.S. Department of Agriculture. Historical arabica coffee yield per hectare data from 1961 to 2018 comes from TILASTO. The occurrence of arabica coffee points is provided by Ovalle-Rivera et al. (2015). Bioclimatic variables come from the Intergovernmental Panel on Climate Change (IPCC) and Worldclim. Unit fertilization and irrigation costs, roasting center capacity, coffee bean loss percentage and demand in states are from existing national and commercial databases. The demand will increase 5% every year (Statista,2019). All of those data are listed in Appendix.

Figure 4-2 shows the historical arabica coffee bean yield of the supply countries from 1961 to 2018. The arabica coffee bean yield was generally increasing over the last 57 years in those countries. For Colombia and Brazil, which are high volume production countries, the high coffee bean production year always followed by a low production year. However, there is a decreasing trend of the future arabica coffee bean yield seen form the latest years.

The based and additional arabica coffee yield is found based on the predicted future yield. The rough relationship between different shade management and management practices with the yield is estimated from existing published researches. According to Soto-Pinto et al. (2000) and H. N. de Souza et al. (2012), coffee bean yield arrives at the highest point in the medium shade cover, then decreasing with shade cover at high level. The function of the relation between yield and shade cover is:

$$Y = 5 + 0.13(shade\ cover) - 0.0013 \times (shade\ cover)^2 - 0.054 \times (\frac{coffee\ density}{100})$$

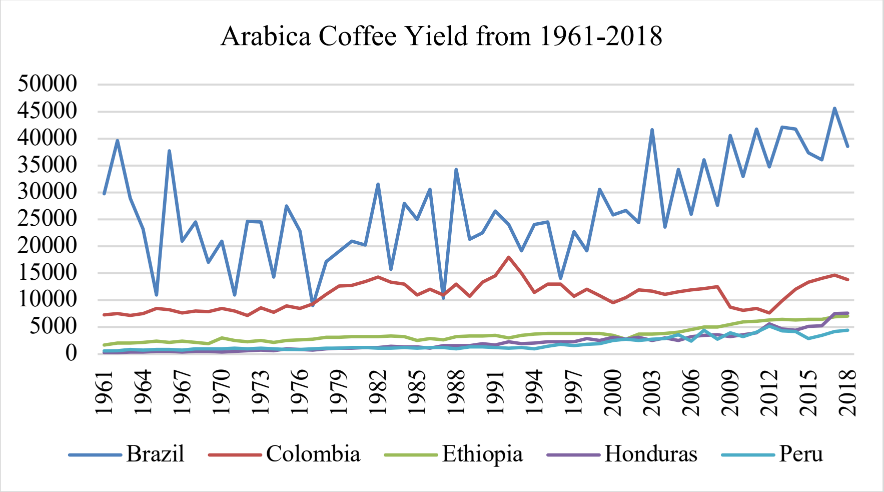


Figure 4-2 Arabica coffee yield from 1961-2018

For the same harvesting field, assuming the coffee density maintains the same level, the ratio of the production of coffee bean yield for unshaded, low shaded, medium shaded, high shaded estimated is 1: 1.1: 1.65: 0.3. Based yield for different shade cover would be the product of predicted yield and the ratio. At the same level of shade cover, the yield increases 67% under full irrigation compare with low irrigation (Rahn et al., 2018). Form the research of Liu et al. (2016), the ratio of the yield of no fertilization with no irrigation, no fertilization with irrigation, fertilization with no irrigation, and fertilization with irrigation would be 1: 1.22: 3: 4. Based on that, the function of additional yield would be based yield × (additional ratio -1).

Arabica coffee yield could be affected by not only weather conditions but also management methods and government policies. To eliminate the interference of non-environmental factors, the future arabica coffee yield per hectare and harvesting area will be considered separately. The total arabica coffee yield is the product of yield per hectare and harvesting area. The next chapter will discuss more details about how to predict the future based yield through the historical yield data and bioclimatic variables. The results of based yield and additional yield under different climate scenarios will be attached in Appendix.

The costs in the coffee bean supply chain come from cultivation and transportation. Table 4-2 shows that unit shade management and management practice costs with different levels of shaded cover and input.

Table 4-3 shows the harvesting area and annul exported coffee beans of suppliers in 2019, which are assumed to maintain the same for the next 30 years.

Table 4-1 Data Sources

Parameters	Sources
Agriculture	
▪ Historical yield/hectare (kg/ha/y) ▪ Current harvesting area (ha) ▪ Annual exported arabica coffee beans (%) ▪ Annual exported arabica coffee beans to U.S. (%)	▪ TILASTO ▪ Coffee Annual - United States Department of Agriculture
Cost	
▪ Unit shade management cost ($/ha/y)	▪ Jezeer et al. (2018b)
▪ Unit management practices cost ($/ha/y)	▪ Jezeer et al. (2018b)
▪ Unit oversea shipping cost ($/kg)	▪ (World Freight Rates 2020)
▪ Unit truck transportation cost ($/kg)	▪ (World Freight Rates 2020)
▪ Unit roasting cost ($/kg)	▪ How Much Should You Pay For Coffee Beans? – JavaPresse Coffee Company
Climate	
▪ Occurrence arabica coffee points (lat, long)	▪ Ovalle-Rivera et al. (2015)
▪ Bioclimatic variables (℃, mm)	▪ IPCC ▪ WorldClim
Others	
▪ Roasting center capacity (kg/y)	▪ Supply Chain 24/7 Paper, 2017 – Starbucks Coffee Distribution Network
▪ Demand (kg/y)	▪ Statista – Coffee Consumption U.S. 2018/2019
▪ Coffee bean loss percentage o Before roasting (%) o After roasting (%)	▪ Transport Information Service – Coffee

Table 4-2 Unit shade management and management practices cost

	Unshaded	Shaded Cover (%)			Input			
		Low	Medium	High	0-0[a]	0-1[b]	1-0[c]	1-1[d]
Cost($/ha/y)	0	1633.59	1404.52	1327.99	0	987.8	1296.23	2049.83

a: no fertilization and no irrigation; b: fertilization and no irrigation; c: no fertilization and irrigation; d: fertilization and irrigation

Table 4-3 Harvesting areas and annul exported coffee beans of suppliers

	Colombia	Brazil	Honduras	Peru	Ethiopia
Harvesting area(ha)	925,440	1,800,400	505,120	423,550	694,330
Annual exported coffee beans (%)	85%	70%	95%	96%	56%

4.3 Scenarios Generation

For arabica coffee yield per hectare climate scenario generation, representative concentration pathway is a CO_2 concentration trajectory adopted by IPCC, which accounts four pathways originally: RCP26, RCP45, RCP 60 and RCP85, with CO_2 equivalent increasing progressively. In this study, GFDL-ESM2M(GE), HadGEM2-ES(HE), IPSL-CM5A-LR(ICL), MIROC5(MI) climate models under representative concentration pathway RCP45 and RCP85 emission scenarios will be investigated (ISIMIP Data Search). And we assume the probability of each climate model is equal.

For arabica coffee suitable harvesting area climate scenario generation, the 19 bioclimatic variables from the Worldclim 2.5 arc minute resolution database will be used in this study. Monthly values were averaged over 20 years periods (2021-2040 and 2041-2060) for 7 global climate models: BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, IPSL-CM6A-LR, MIROC-ES2L and MIROC6 for Shared Socio-Economic Pathways 585.

5 Numerical Experiments

5.1 Future Yield Prediction

K-nearest Neighbor, which is an effective machine-learning algorithm to predict the numerical target based on Euclidean distance function, is adopted for future arabica coffee bean yield per hectare prediction. The optimal k value of a testing data's closet neighbors in the feature space is found by experiments for specific training data, default setting the k value as k=1, generating prediction based on k nearest neighbors and increasing k with length 1 until the best performance of the prediction. We develop the regression model using historical meteorological data (monthly average temperature (℃) and precipitation (mm)) in harvesting seasons and historical arabica coffee yield per hectare from 1961 to 2018 with splitting 80% as training subset and 20% as testing subset. R square is used to evaluate the performance of each model. After getting the regression model, we fit the regression model with future meteorological data $x(t)$ to get future yield per hectare $Y(t)$. Therefore, the prediction model can be expressed as:

$$Y(t) = regression\,model(x(t), k)$$

In Colombia, the harvesting seasons sustain the whole year. In Brazil, the harvesting seasons are July, August and September. In Honduras, the harvesting seasons are October, November and December. In Peru, the harvesting seasons are April, May and June. In Ethiopia, the harvesting seasons are October, November and December. Besides the weather condition, yield per hectare is also affected by some other reasons like management methods and governmental policies. Detrended fluctuation analysis is a method in time series analysis to remove the linear trend. Table 5-1 shows the best-fitted trendline equations y of these five countries. Given a time series trended yield per hectare x_t of length T, where t ∈ T, detrended yield per hectare X_t is:

$$X_t = x_{2021} + x_t - y$$

Table 5-1 Historical yield per hectare trendline equation

Country	Trendline Equation	R-square
Honduras	$y = 1.263x + 29.662$	0.9216
Peru	$y = -0.00254x^3 + 0.282x^2 - 3.5817x + 532.25$	0.6047
Colombia	$y = -0.115x^2 + 13.577x + 488.79$	0.5537
Brazil	$y = 0.56x^2 - 15.049x + 566.97$	0.8617
Ethiopia	$y = -0.235x^2 + 24.058x + 100.78$	0.8222

In this research, we will predict both trended and detrend arabica coffee yield per hectare from 2021 to 2050 of 4 climate models: GE, HE, ICL and MI under RCP45 and RCP84 emission scenarios, which are shown as follow:

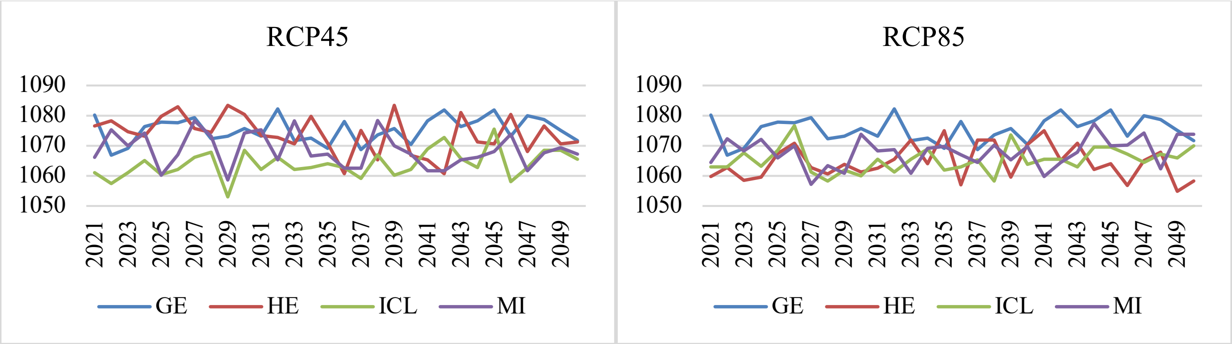


Figure 5-1 Detrended Honduras predicted arabica coffee bean yield/hectare (kg/ha) from 2021-2050

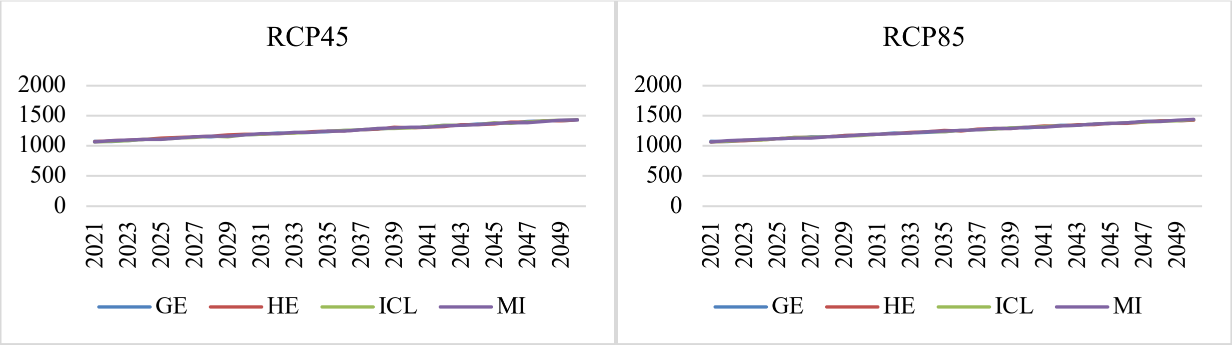


Figure 5-2 Honduras predicted arabica coffee bean yield/hectare (kg/ha) from 2021-2050

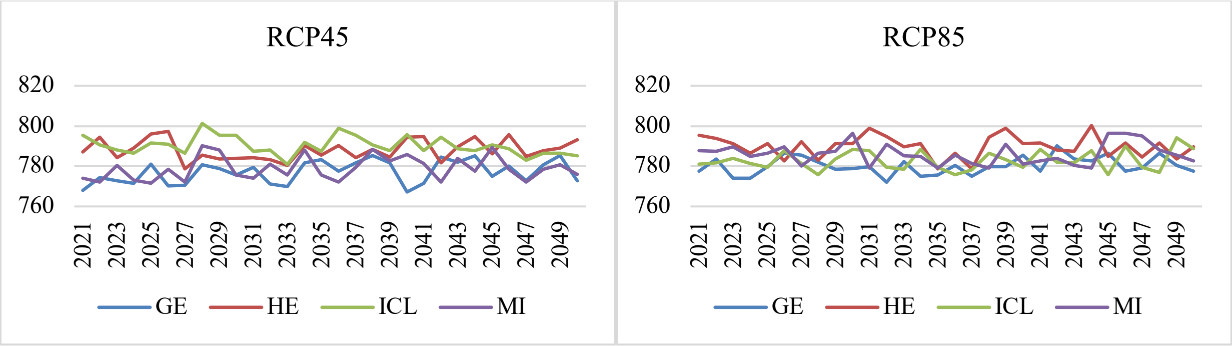


Figure 5-3 Detrended Peru predicted arabica coffee bean yield/hectare (kg/ha) from 2021-2050

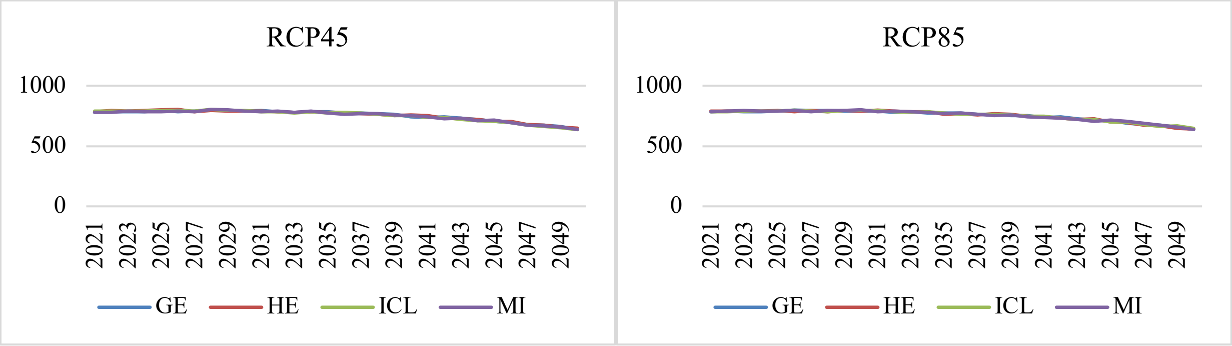


Figure 5-4 Peru predicted arabica coffee bean yield/hectare (kg/ha) from 2021-2050

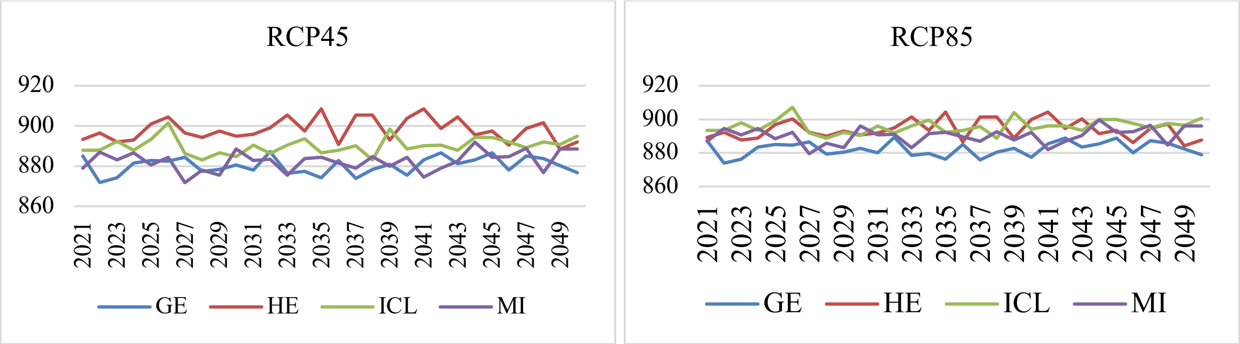


Figure 5-5 Detrended Colombia predicted arabica coffee bean yield/hectare (kg/ha) from 2021-2050

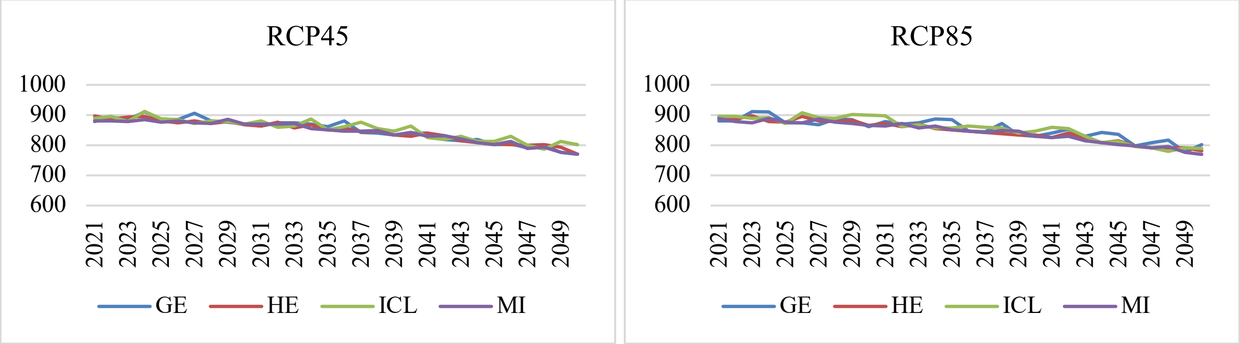


Figure 5-6 Colombia predicted arabica coffee bean yield/hectare (kg/ha) from 2021-2050

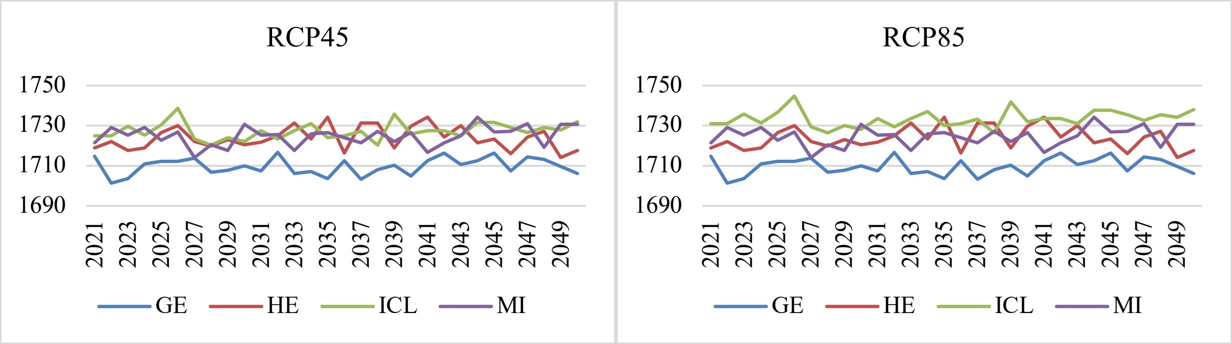


Figure 5-7 Detrended Brazil predicted arabica coffee bean yield/hectare (kg/ha) from 2021-2050

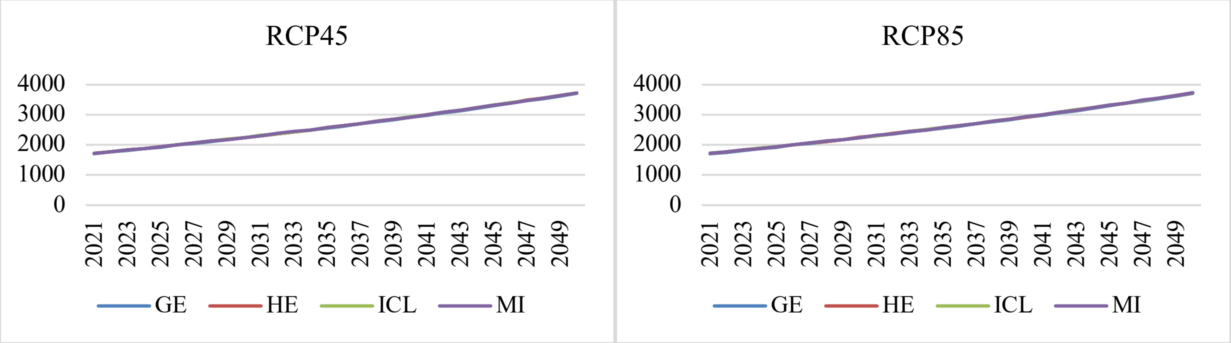


Figure 5-8 Brazil predicted arabica coffee bean yield/hectare (kg/ha) from 2021-2050

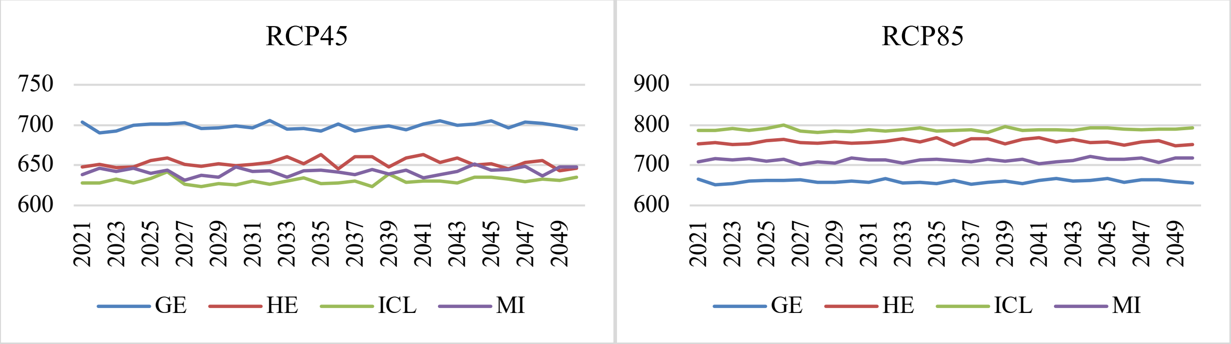


Figure 5-9 Detrended Ethiopia predicted arabica coffee bean yield/hectare (kg/ha) from 2021-2050

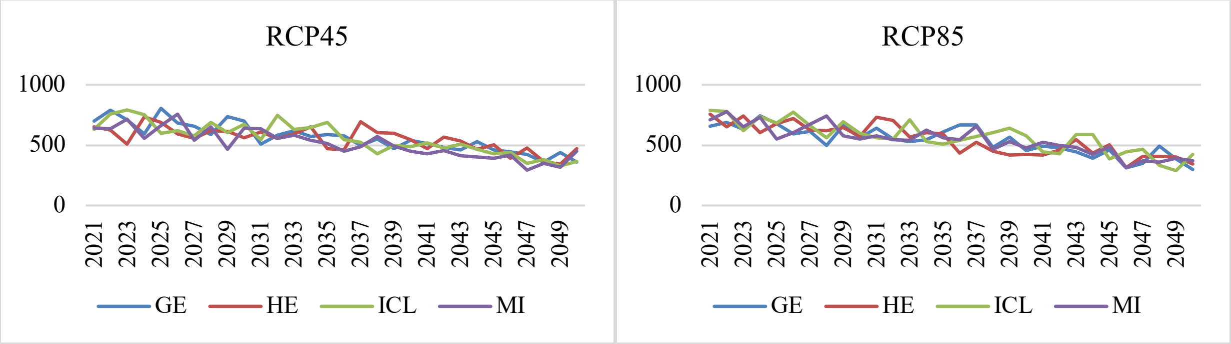
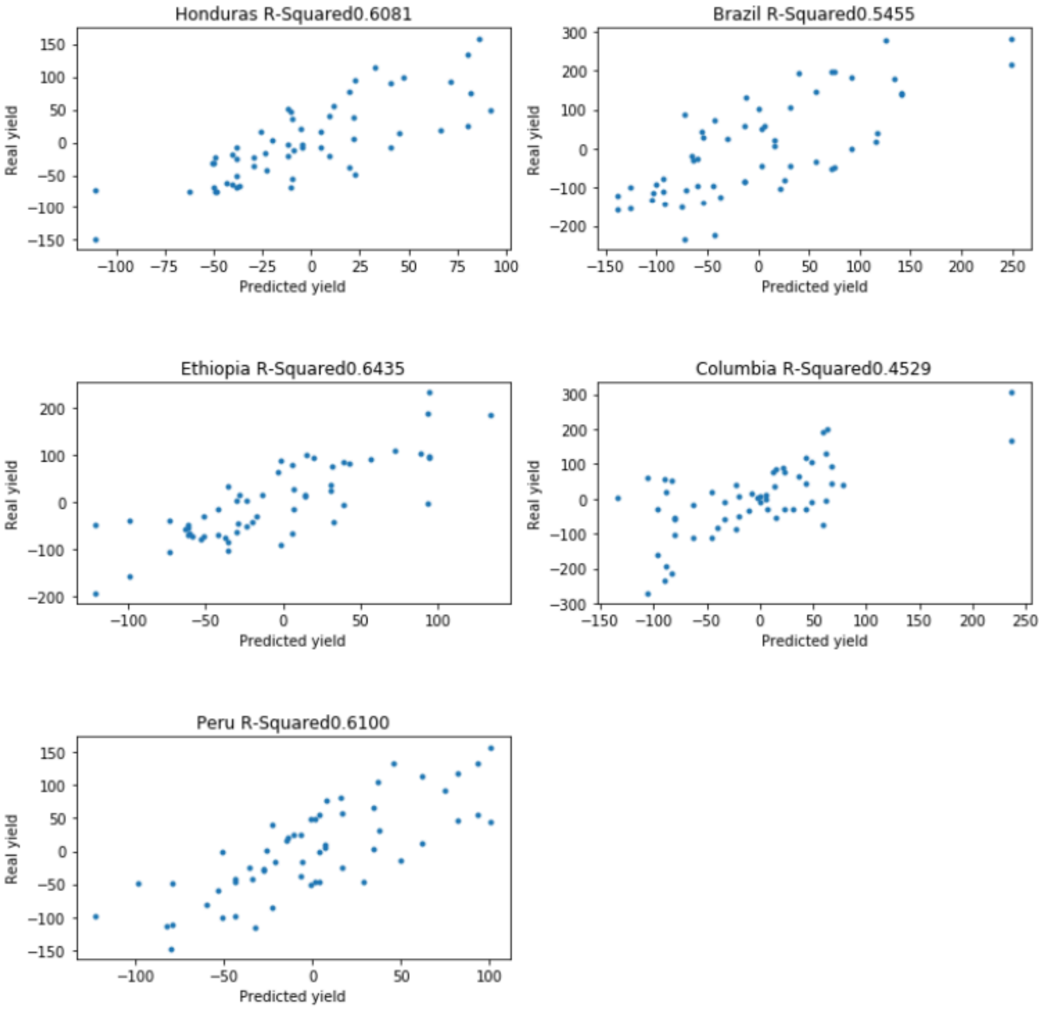


Figure 5-10 Ethiopia predicted arabica coffee bean yield/hectare (kg/ha) from 2021-2050

The R-squared results of each regression are showing in Figure 5-6. Most of the R-squared scores are reasonable. Besides, in Colombia, the prediction might be less accurate because the R-squared scores are smaller than 0.5.

From the result, the trended predictions show that in Peru, Colombia, and Ethiopia, the arabica coffee yield per hectare will decrease every year. While in Brazil and Honduras, the arabica coffee yield per hectare will increase gradually from 2021 to 2050.


Honduras R-Squared0.6081

Brazil R-Squared0.5455

Ethiopia R-Squared0.6435

Columbia R-Squared0.4529

Peru R-Squared0.6100

Figure 5-11 R-squared of KNN regression for arabica coffee bean yield per hectare prediction

According to some literature references and news, the historical yield per hectare increased dramatically in Brazil and Honduras affected by some other reasons, not just because of weather conditions. In the 20th Century, Brazilian coffee cultivation was extended rapidly from south to north, and the coffee economy was tightly bound with the Brazilian economy. The coffee market was highly regulated by the Brazilian government during the mid-1990s (Volsi et al., 2019). In Honduras, farmers harvest more coffee, and higher coffee prices have doubled the coffee production in less than ten years (Analysis, 2012).

In this study, the only uncertainty is climate condition, other impact factors of the arabica coffee yield per hectare like management methods and government policies are assumed to remain unchangeable. Therefore, comparing with trended values, the fluctuation of detrended predicted yield per hectare values in different weather conditions is more reasonable to use. Since the arabica coffee yield per hectare will not increase without limit. If farmers do not implement new technology, the increasing trend will not maintain. Therefore, in the next numerical experiment, we will use the detrend data to do the calculation and provide policy recommendations for farmers and coffee beverage companies based on this assumption.

The Maxent algorithm for modeling species niches and distributions, which has been proven more useful for analyzing the impact of climate change on coffee than other models, will be used to predict the future suitable areas for arabica coffee trees in this study. Studies about the effect of climate change for arabica coffee production have shown that the future suitable areas for coffee trees will shift from low latitudes to higher latitudes due to increasing temperature and changeable precipitation. It will damage the coffee production in some regions a lot, while some regions could also benefit from that. The global distribution of arabica coffee under changes in suitability in the 2030s and 2050s projected by seven global climate models is modeled. The suitability in the 2030s is predicted with the downscaled monthly future climate data for the period from 2021 to 2040, and the suitability in 2050s is predicted with the period from 2041 to 2060. We train the Maxent algorithm using the presence locations where arabica coffee grows and 20,000 random background locations. Then we apply the derived suitability function to each of the 7 global climate models in the 2030s and 2050s. Figure 5-12 shows the suitable locations used for prediction and the suitable areas for arabica coffee in one of the climate models in 2050. Comparing these two maps, the suitable area in Honduras, Peru, Colombia, and Brazil will decrease, and Ethiopia will increase.

To validate the model, we use 10 replicate runs. 80% of the presence locations are selected randomly to train the model and 20% to test the predictive performance. The model performs well with AUC values 0.9-0.94 for test data, and 0.93 for training data shows in Table 5-2.

We use Jenks natural breaks classification method to determine the suitability values into 4 classes, high suitable area, medium suitable area, low suitable area and not suitable area. For the average of these 7 climate models, Honduras would lose 28% suitability, Peru would lose 22% suitability, Colombia would lose 8% suitability, Brazil would lose 27% suitability and Ethiopia would increase 7% suitability by 2050 shown in Table 5-3.

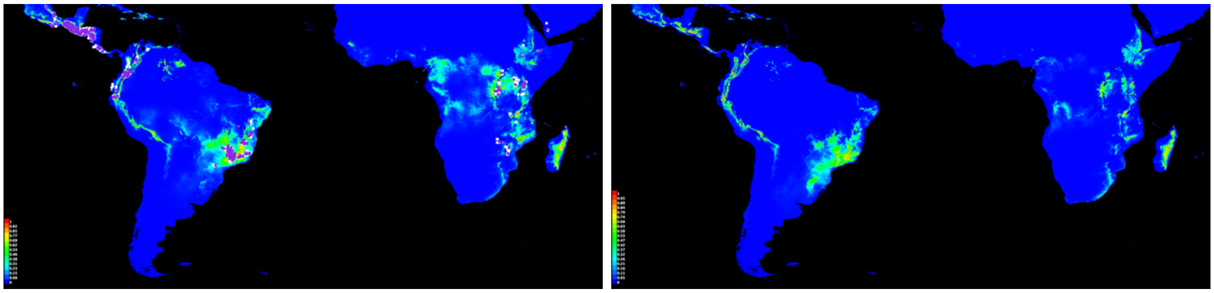
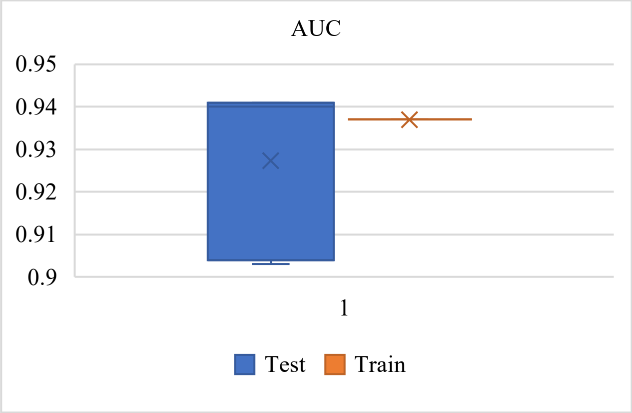


Figure 5-12 Suitable locations used for analysis and suitable locations for arabica coffee in 2050

Table 5-2 Performance of the Maxent model across 10 replicates



After getting the suitable growing area in 2030 and 2050, we use linear interpolation to calculate other growing areas from 2021 to 2050. The result is listed in Appendix. The future arabica coffee total yield under GFDL-ESM2M (GE), HadGEM2-ES(HE), IPSL-CM5A-LR(ICL), MIROC5(MI) climate models under representative concentration pathway RCP45 and RCP85 emission scenarios from 2021 to 2050 is the product of yield per hectare under these 8 climate scenarios and the average suitable growing area. After getting the total yield, based yield and additional yield can be calculated as we mentioned before. The results are listed in Appendix. The next section is talking about the optimal solutions for coffee bean supply chain planning under different climate scenarios.

5.2 Comparison under Different Climate Scenarios

The experiment is carried out using Gourbi – an open-source optimization solver for programming. The two-stage stochastic model is constructed based on all the data and parameters that mentioned earlier. The objective is minimizing the total cost includes cultivation cost, transportation cost and shortage cost of the coffee supply chain process.

Table 5-3 Changes in suitability and area (ha) of arabica coffee in 5 supply countries by 2050s

Country	Current harvesting area (ha)	Suitable growing area in 2030 (ha)	Suitable growing area in 2050 (ha)	The average change in suitability by 2050s		
				Average	Min	Max
Honduras	349,000	276,209	220,867	-0.28	-0.39	-0.15
Peru	388,000	316,497	294,326	-0.22	-0.31	-0.08
Colombia	925,440	893,711	807,777	-0.08	-0.19	0.06
Brazil	1,800,400	1,437,748	1,159,972	-0.27	-0.48	-0.1
Ethiopia	694,330	786,577	702,265	0.07	-0.11	0.21

For the comparison purpose, the annual arabica coffee supply chain planning under different climate scenarios is shown in Figure 5-13. Figure 5-13 shows the results of shade management and management practices planning from 2021-2050 under 4 climate scenarios in path RCP45 and RCP85. When based yield cannot meet the demand, the model will choose a shade management method with higher yield. Then, when the based yield cannot meet the demand, the model will adjust the management practices to improve the yield. We observe that the shade management should be applied in the medium level shade, which has the highest based yield in all of these five countries in both climate scenario RCP45 and RCP85. Management practices planning will change according to the climate condition, and consumer demand in the market, which is increasing 5% annually in this experiment. As mentioned earlier, the future arabica coffee yield will decrease in Honduras, Peru, Colombia and Brazil. In Ethiopia, the arabica coffee yield will increase from 2021 to 2036 and decrease from 2037 to 2050. The total based yield could not meet the demand in 2021, and the model starts to implement management practices in Colombia first. With the demand increasing and supply decreasing, the need for fertilization and irrigation is increasing. Though all the supply countries are using the best shade management and management practices, the supply still cannot meet the demand in some years, so Starbucks will have shortage in the future. The shortage under different consumption demand and different climate scenarios will be discussed in the next section.

Figure 5-14 shows the most cost-efficient supply chain logistics network for arabica coffee bean to be delivered from Honduras, Peru, Colombia, Brazil and Ethiopia to 48 states and Washington, D.C. where have Starbucks coffee shop. Five ports: Port of Seattle, Port of Oakland,

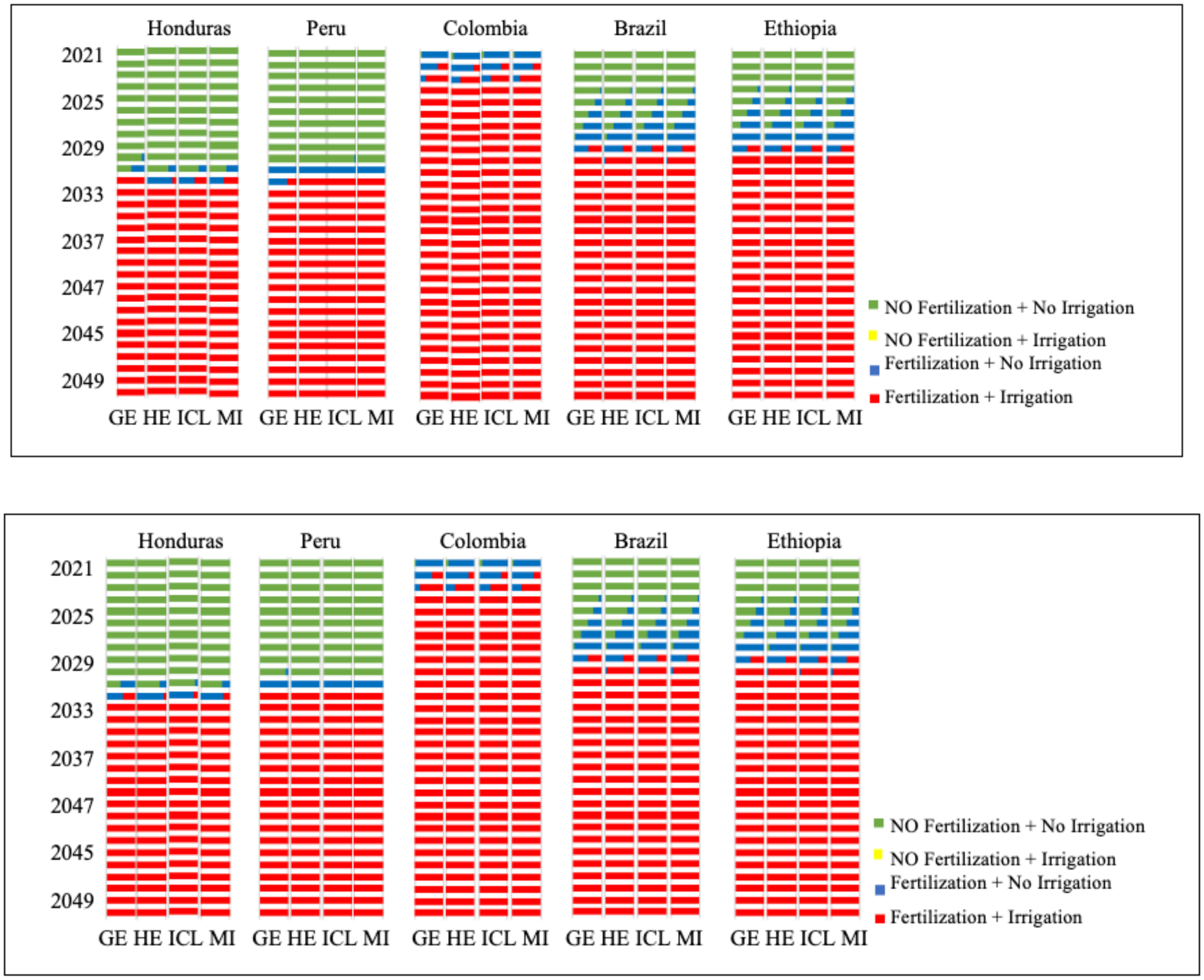


Figure 5-13 Management practices planning under RCP45 path and RCP85 path

Port of New York, Port of Charleston and Port of Jacksonville are chosen to form the top 10 U.S. ports. This transportation map only considers the unit transportation cost. The result indicates that for all the transportation process, the shortest route will always be chosen at first. From supply countries to ports in the U.S., Ethiopia and Peru will ship the arabica coffee beans to the ports in Seattle and Oakland on the west coast. Honduras, Colombia and Brazil will ship the arabica coffee beans to both sides of the coast. Then each port will transport the arabica coffee beans to the nearest roasting center, the route is: Seattle to Kent, Oakland to Minden, New York to York, Charleston to Gaston and Jacksonville to Augusta. After roasting, the roasted arabica coffee beans will be delivered to the nearest state. Since it is too complicated to consider every Starbucks' coffee stores, we use the capital city as the destination to calculate the distance between the roasting centers and states.

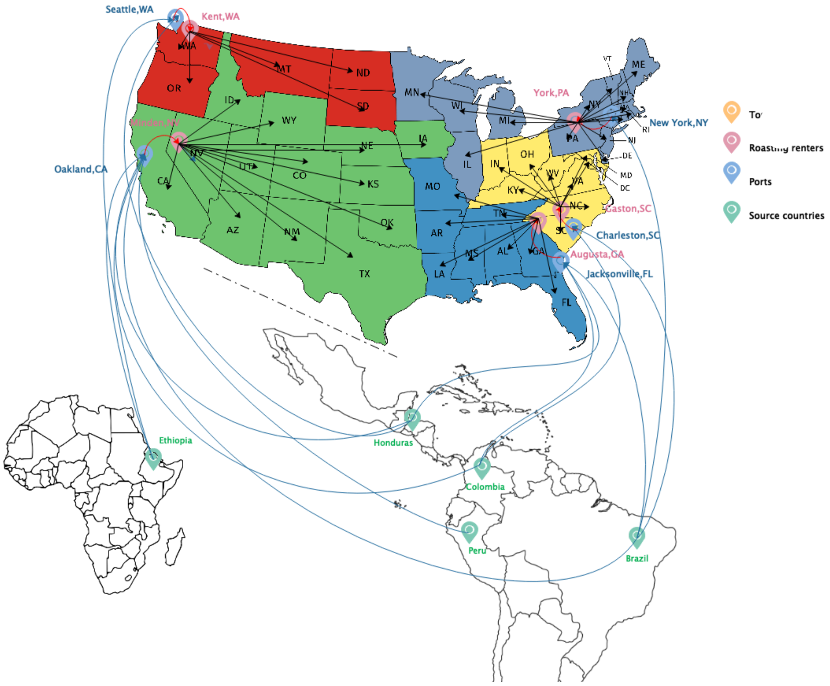


Figure 5-14 Starbucks coffee bean supply chain logistics network

5.3 Parameters Sensitivity Analysis

We already known that the arabica coffee beans supply could not meet the demand from the result above. The demand increasing rate is obtained from a business report of Starbucks, and it could be smaller, or bigger than 5% impacted by many events. With the changing of demand, the shortage will change as well. Therefore, in this section, the average shortage under climate model HE, GE, ICL and MI in RCP45 and RCP85 with demand increase 3%, 5% and 7% are estimated and shown in Figure 5-15.

When the demand increase, shortages will happen earlier. When the demand increases 3% annually, Starbucks will start to have shortage from 2039. If the demand increases 7% annually, Starbucks will have shortage from 2025. When we consider the increasing amount of coffee consumption around the world, the shortage will become inevitable for the whole coffee industry. To reduce loss, the coffee shops could increase the retail price of a cup of coffee and drinking coffee could become an expensive event. The decreasing of arabica coffee yield will also threat smallholders' livelihood in those poor coffee growing countries. Therefore, it is everyone's responsibility to face this coffee crisis caused by climate change. In the next section, we will talk about some policy recommendations for the local government, international coffee organizations and coffee beverage companies.

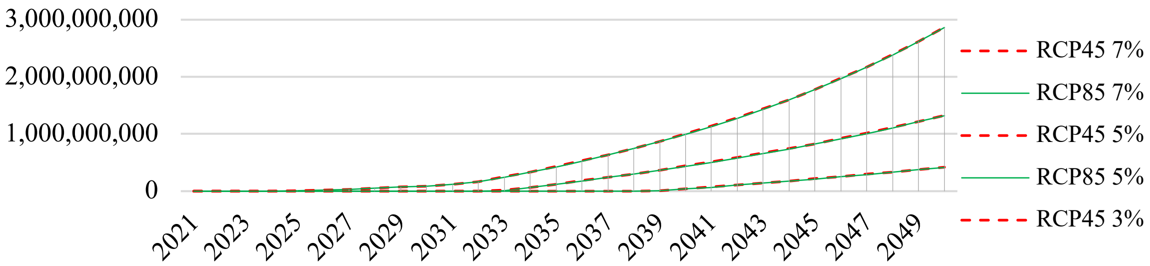


Figure 5-15 Shortage under different demand in RCP45 and RCP85

6 Discussion

6.1 Suitability Policy Recommendations for Coffee Supply Chain Management

In the next few decades, the production of arabica coffee based on our study, could not meet the consumption demand, which will hurt both arabica coffee growing countries' economy and coffee beverage companies' profit. It's the responsibility of everybody in the coffee community to enhance coffee sustainability, which covers environmental, economic and social dimensions.

Environmental sustainability mainly concerns about water conservation, forests conservation and restoration, natural disease and agricultural pests. Frist, sufficient precipitation is the essential requirement for coffee growing. Unpredictable rainfall could reduce the plantations' productivity. Building irrigation infrastructure could help farmers to supply extra water for coffee trees during dry seasons. The wet process of making coffee berry to green coffee beans needs substantial quantities of water. Therefore, more water saving methods or investment are needed. Second, growing coffee under variable trees could protect coffee trees from high temperature and too much sun and provide more natural nutrition for coffee trees. Forests conservation provides local tree species for shading. Third, possible solutions for natural disease and agricultural pests are also identified and discussed in some researches. Shade management, no chemical pesticide use, and plant fertilization are important considerations.

About the economic aspect, since most of the farmers do not have enough money to invest in their farms. Financial support from government and coffee beverage companies, such as loan products and insurance for farmers, could help them get new disease-resistant coffee bean seeds, apply advanced management techniques, and improve farm infrastructure. Then, certificated coffee, includes: Fair Trade Certified, Rainforest Alliance, Smithsonian Bird Friendly, USDA Organic and Utz Certified could tell consumers about the farming practices so that coffee beans can be sold at a higher price. In return, buyers could have the opportunity to sell coffee drink at higher retail price and improve economic sustainability. Selling and buying coffee with sustainability certifications could not only improve farmers' income but also bring a better reputation and higher profit to coffee beverage companies.

In most coffee producing countries, farmers work and live under extremely poor conditions. They are at the risk of being poisoned by pesticides and injured by cutting tools in the harvesting process, suffered air and noisy pollution in the processing coffee berry process. There is also discrimination against women and child labor issues. Therefore, in social sustainability for coffee supply chain aspect, the local government, international organization and coffee beverage companies could help with technical assistance, education, health care, living condition and labor condition. International organization and coffee beverage companies could provide technical assistance includes doing research for new coffee bean type, teaching agricultural knowledge and management techniques for farmers could improve both quality and quantity of coffee beans and save more money. The local government need to provide education for children, promote equal pay for equal work for women, and implement medical care for everyone.

6.2 Future Improvement

The modeling of arabica coffee yield is not complex in this study. The analysis of arabica coffee yield per hectare under different climate scenarios only considers the monthly average temperature and precipitation in harvesting seasons using KNN regression. The R^2 of the regression models are not high enough. In the real world, the yield per hectare data does not follow the typical theoretical assumptions. Since there are not enough high temperature and low yield training data in the historical datasets for the model to learn, the prediction may not be accurate when the temperature significantly increases in the future. The historical fluctuation in temperature are not significant enough to capture the relationship between the climate features and yield per hectare. In the real world, it is hard to predict crop yield in a long-term period due to the large variability weathers. The crop yield could be affected by many factors, such as climate, technology, management method, policy, and price. In future research, the accuracy of arabica coffee yield model could be improved by using more factors through better analysis methods like Global Change Analysis Model.

Supply chain model structure and parameters in this study may differ from the real world. We tried to address this issue in our sensitivity analysis section via adjusting parameter values. Some parameters, like coffee price, inventory and labor cost, which may affect the coffee supply chain planning, have not been considered in this study. In future research, coffee price, inventory and labor cost could be considered in the model to see the impact of climate change on those variables.

Pests and leaf diseases could damage the coffee yield a lot, which already happened in some regions. Climate change will increase the risk of agricultural pests and diseases like coffee white stem borer. In the future research, these risks could also be considered.

7 Conclusion

In this study, optimization for arabica coffee supply chain planning under climate change is studied with the objective of minimizing the cultivation and transportation cost. We establish a two-stage stochastic model for arabica coffee supply chain with uncertain climate scenarios first. Then we used a real-world global coffee beverage company as the case study. The arabica coffee yield per hectare from 2021 to 2050 was predicted using k-nearest neighbors regression. The average monthly temperature and precipitation in the harvesting seasons are the most significant features in this regression model. The future suitable harvesting area was predicted using the Maxent algorithm, a species distribution model. Multiply yield/hectare by harvesting area is the total yield. The numerical experiment result shows that in Honduras, Peru, Colombia and Brazil, the arabica coffee yield will decrease from 2021 to 2050, in Ethiopia it will increase for several years and start to decrease for the next years. Arabica coffee production in these countries will not meet the coffee company's demand gradually. Medium-level shade management should be applied at the beginning, the percentage of the filed where apply management practices will increase as well.

Most of coffee growing plantations are owned by smallholders in the poor courtiers. They do not have enough money and technology to face this risk. Fortunately, lots of coffee beverage companies and organizations already realized the importance of developing a sustainable coffee business and start to help those farmers and plantations. In this study, we suggest several policy recommendations in environmental, economic, and social aspects for different participators in the coffee supply chain. However, no single policy is likely to meet the range of conditions on the ground. The coffee supply chain planning in the case study ignores the different climate conditions and future yield trend in different countries with the objective of minimizing the total cost. In some countries, the yield decline will be worse than other locations, but the coffee supply chain planning model does not consider that. Therefore, in those countries, the local government should come up with more adoption policies and strategies based on their own situations to face this crisis.

In future research, more factors of coffee yield prediction should be considered, and more complex interaction between the agents in the supply chain model will be focused.

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Appendix

Table A - 1 Colombia predicted coffee bean yield (Tons) from 2021-2050

	RCP45				RCP85			
	GE	HE	ICL	MI	GE	HE	ICL	MI
2021	816,329,041	823,750,372	818,756,489	810,615,731	818,290,380	819,927,888	824,016,839	817,831,783
2022	801,278,373	823,822,452	815,939,666	815,091,803	803,232,965	820,013,119	821,181,919	822,283,029
2023	800,666,457	816,992,281	817,409,584	808,686,214	802,614,302	813,196,099	822,633,739	815,852,614
2024	804,431,943	815,166,807	810,384,380	809,344,442	806,373,039	811,383,775	815,590,438	816,486,016
2025	802,933,458	819,422,362	812,452,841	800,844,206	804,867,807	815,652,481	817,640,802	807,960,954
2026	799,987,050	819,711,757	817,040,689	801,671,097	801,914,651	815,955,027	822,210,552	808,763,019
2027	798,725,777	809,602,271	800,363,192	787,366,263	800,646,630	805,858,692	805,514,957	794,433,359
2028	789,644,799	804,844,580	794,781,192	790,226,638	791,558,905	801,114,152	799,914,860	797,268,908
2029	787,600,035	804,793,324	795,242,106	785,130,553	789,507,393	801,076,047	800,357,676	792,147,997
2030	786,992,313	799,720,973	790,761,667	793,994,711	788,892,923	796,016,846	795,859,139	800,987,330
2031	780,938,822	796,848,334	791,805,144	785,275,424	782,830,295	793,162,016	796,878,109	792,234,424
2032	785,260,259	795,749,327	784,311,364	781,841,048	787,142,594	792,080,817	789,359,823	788,766,429
2033	772,077,530	797,557,322	784,154,853	771,069,031	773,950,727	793,906,619	789,178,804	777,960,795
2034	769,094,297	786,627,040	783,291,700	774,582,429	770,958,357	782,994,146	788,291,145	781,440,574
2035	762,470,692	792,398,887	773,379,982	771,304,737	764,325,614	788,783,802	778,354,919	778,129,263
2036	766,298,612	772,984,007	770,518,399	765,189,784	768,144,397	769,386,730	775,468,829	771,980,693
2037	754,557,810	781,995,227	768,604,421	759,156,139	756,394,457	778,415,758	773,530,344	765,913,429
2038	754,880,271	778,104,704	758,824,581	760,306,682	756,707,781	774,543,043	763,725,997	767,030,353
2039	753,071,779	763,574,485	768,171,575	752,222,336	754,890,151	760,030,632	773,048,484	758,912,389
2040	744,701,394	769,027,847	755,936,950	752,307,083	746,510,629	765,501,802	760,789,352	758,963,518
2041	747,516,112	768,978,230	753,530,495	740,061,746	749,316,209	765,469,995	758,358,390	746,684,562
2042	746,757,819	756,740,783	749,728,542	740,271,657	748,548,778	753,250,356	754,531,930	746,860,856
2043	738,329,999	757,755,122	743,817,266	739,356,870	740,111,821	754,282,503	748,596,147	745,912,449
2044	736,132,618	746,534,147	745,436,402	743,438,200	737,905,302	743,079,336	750,190,775	749,960,162
2045	735,327,852	744,210,876	741,593,946	733,442,526	737,091,399	740,773,874	746,323,813	739,930,869
2046	724,361,922	734,485,286	735,839,225	729,894,414	726,116,331	731,066,092	740,544,584	736,349,139
2047	726,301,867	737,406,915	729,798,396	729,386,340	728,047,138	734,005,529	734,479,248	735,807,447
2048	721,347,014	735,884,924	728,174,233	715,812,592	723,083,148	732,501,346	732,830,578	722,200,080
2049	714,667,955	721,407,098	723,316,210	721,466,348	716,394,952	718,041,329	727,948,048	727,820,218
2050	708,186,204	720,435,483	722,806,680	717,649,066	709,904,064	717,087,522	727,414,011	723,969,317

Table A - 2 Brazil predicted coffee bean yield (Tons) from 2021-2050

	RCP45				RCP85			
	GE	HE	ICL	MI	GE	HE	ICL	MI
2021	3,024,892,516	3,032,469,944	3,043,203,773	3,036,614,779	3,024,892,516	3,032,469,944	3,053,948,881	3,036,614,779
2022	2,939,695,041	2,975,595,015	2,980,644,838	2,987,849,066	2,939,695,041	2,975,595,015	2,991,169,060	2,987,849,066
2023	2,881,974,315	2,905,780,121	2,926,003,035	2,918,505,469	2,881,974,315	2,905,780,121	2,936,306,371	2,918,505,469
2024	2,832,048,817	2,845,307,200	2,855,669,080	2,862,211,937	2,832,048,817	2,845,307,200	2,865,751,529	2,862,211,937
2025	2,772,314,579	2,795,591,304	2,801,803,483	2,789,383,936	2,772,314,579	2,795,591,304	2,811,665,046	2,789,383,936
2026	2,709,964,215	2,738,470,548	2,752,007,318	2,733,227,652	2,709,964,215	2,738,470,548	2,761,647,994	2,733,227,652
2027	2,650,509,100	2,663,330,281	2,665,294,889	2,650,915,943	2,650,509,100	2,663,330,281	2,674,714,679	2,650,915,943
2028	2,577,827,214	2,597,666,255	2,598,147,161	2,598,194,928	2,577,827,214	2,597,666,255	2,607,346,065	2,598,194,928
2029	2,517,142,192	2,539,869,215	2,541,122,011	2,532,009,408	2,517,142,192	2,539,869,215	2,550,100,028	2,532,009,408
2030	2,458,717,650	2,473,800,944	2,475,920,791	2,488,442,826	2,458,717,650	2,473,800,944	2,484,677,921	2,488,442,826
2031	2,431,332,343	2,451,460,110	2,459,759,817	2,456,556,601	2,431,332,343	2,451,460,110	2,468,432,353	2,456,556,601
2032	2,420,509,998	2,431,929,230	2,429,922,450	2,433,166,761	2,420,509,998	2,431,929,230	2,438,510,391	2,433,166,761
2033	2,381,814,465	2,416,961,889	2,411,773,173	2,398,141,173	2,381,814,465	2,416,961,889	2,420,276,519	2,398,141,173
2034	2,359,353,898	2,381,815,935	2,392,450,626	2,385,754,977	2,359,353,898	2,381,815,935	2,400,869,377	2,385,754,977
2035	2,331,169,736	2,372,986,223	2,358,884,854	2,362,596,622	2,331,169,736	2,372,986,223	2,367,219,010	2,362,596,622
2036	2,319,342,299	2,324,693,751	2,336,420,917	2,335,002,137	2,319,342,299	2,324,693,751	2,344,670,478	2,335,002,137
2037	2,283,223,032	2,320,782,123	2,315,412,071	2,307,572,375	2,283,223,032	2,320,782,123	2,323,577,038	2,307,572,375
2038	2,265,860,467	2,296,737,182	2,282,228,041	2,291,271,236	2,265,860,467	2,296,737,182	2,290,308,413	2,291,271,236
2039	2,245,157,051	2,256,357,051	2,278,510,635	2,260,708,091	2,245,157,051	2,256,357,051	2,286,506,412	2,260,708,091
2040	2,214,401,666	2,246,668,941	2,241,618,547	2,242,690,403	2,214,401,666	2,246,668,941	2,249,529,729	2,242,690,403
2041	2,200,705,535	2,228,466,009	2,219,791,390	2,205,887,780	2,200,705,535	2,228,466,009	2,227,617,977	2,205,887,780
2042	2,181,501,519	2,191,800,548	2,195,833,276	2,188,031,980	2,181,501,519	2,191,800,548	2,203,575,268	2,188,031,980
2043	2,150,735,774	2,175,166,586	2,168,709,731	2,168,418,474	2,150,735,774	2,175,166,586	2,176,367,128	2,168,418,474
2044	2,129,345,588	2,140,195,804	2,152,855,534	2,156,205,902	2,129,345,588	2,140,195,804	2,160,428,337	2,156,205,902
2045	2,109,991,352	2,118,548,599	2,128,806,258	2,122,981,504	2,109,991,352	2,118,548,599	2,136,294,467	2,122,981,504
2046	2,075,610,843	2,085,966,789	2,101,939,391	2,099,369,496	2,075,610,843	2,085,966,789	2,109,343,004	2,099,369,496
2047	2,060,259,200	2,072,011,423	2,074,688,820	2,080,204,134	2,060,259,200	2,072,011,423	2,082,007,839	2,080,204,134
2048	2,034,769,883	2,051,465,386	2,053,905,228	2,041,968,021	2,034,769,883	2,051,465,386	2,061,139,651	2,041,968,021
2049	2,006,809,881	2,012,147,562	2,028,405,736	2,031,708,955	2,006,809,881	2,012,147,562	2,035,555,565	2,031,708,955
2050	1,979,188,011	1,992,426,326	2,009,170,199	2,007,670,330	1,979,188,011	1,992,426,326	2,016,235,433	2,007,670,330

Table A - 3 Honduras predicted coffee bean yield (Tons) from 2021-2050

	RCP45				RCP85			
	GE	HE	ICL	MI	GE	HE	ICL	MI
2021	369,120,377	367,870,465	362,613,670	364,349,202	369,120,377	362,120,704	363,249,920	363,726,450
2022	356,802,872	360,645,942	353,663,601	359,608,136	356,802,872	355,464,486	355,512,178	358,622,118
2023	349,806,540	351,552,083	347,112,454	350,047,119	349,806,540	346,303,954	349,305,638	349,533,752
2024	344,315,309	343,282,038	340,689,111	343,598,210	344,315,309	338,951,056	340,064,154	342,969,352
2025	336,926,275	337,541,292	331,491,430	331,392,632	336,926,275	333,674,471	334,004,863	333,210,441
2026	329,031,778	330,659,374	324,276,965	325,798,827	329,031,778	326,965,062	328,727,521	326,671,065
2027	321,695,339	320,587,726	317,741,565	321,369,843	321,695,339	316,780,963	316,331,018	315,088,762
2028	311,811,399	312,412,371	310,521,572	312,016,390	311,811,399	308,426,044	307,710,307	309,210,984
2029	304,238,987	307,132,886	298,518,984	300,105,963	304,238,987	301,585,428	301,038,283	300,739,855
2030	297,100,325	298,416,100	295,153,579	296,697,309	297,100,325	293,153,871	292,793,267	296,615,703
2031	293,426,109	293,477,188	290,414,274	294,017,713	293,426,109	290,515,926	291,349,662	292,137,119
2032	292,932,027	290,361,419	288,570,637	288,351,526	292,932,027	288,417,191	287,279,479	289,290,712
2033	287,087,233	286,803,144	284,536,621	288,872,675	287,087,233	287,193,566	285,453,079	284,211,328
2034	284,358,913	286,291,004	281,805,811	282,775,217	284,358,913	282,097,836	283,400,762	283,476,394
2035	280,532,904	280,984,002	279,195,391	280,009,312	280,532,904	282,049,933	278,616,596	280,674,166
2036	279,842,740	275,367,948	275,923,817	275,820,221	279,842,740	274,435,728	275,961,823	277,021,522
2037	274,496,514	276,127,891	272,051,277	272,905,999	274,496,514	275,328,492	273,585,608	273,401,005
2038	272,744,463	270,651,443	271,086,465	273,984,829	272,744,463	272,362,224	268,877,182	271,912,351
2039	270,351,832	272,265,795	266,450,109	268,867,461	270,351,832	266,268,843	269,811,174	267,692,221
2040	266,035,245	265,141,379	263,964,838	265,243,975	266,035,245	266,051,127	264,393,802	265,873,770
2041	264,982,700	261,808,534	262,687,594	260,923,181	264,982,700	264,202,403	261,860,010	260,461,403
2042	262,875,428	257,757,515	260,672,429	258,013,556	262,875,428	258,823,025	258,918,453	258,673,493
2043	258,558,014	259,688,195	256,049,103	255,925,921	258,558,014	257,273,697	255,372,008	256,548,639
2044	256,032,580	254,394,562	252,381,592	253,171,059	256,032,580	252,220,730	253,978,563	255,836,572
2045	253,895,379	251,279,350	252,426,634	250,661,108	253,895,379	249,713,344	251,019,123	251,111,045
2046	248,890,164	250,583,339	245,421,418	249,035,077	248,890,164	245,119,091	247,522,058	248,221,401
2047	247,516,057	244,777,094	243,541,487	243,323,617	247,516,057	244,078,830	243,952,363	246,179,719
2048	244,207,905	243,726,259	241,930,037	241,738,637	244,207,905	241,780,329	241,616,007	240,501,931
2049	240,429,401	239,429,320	238,973,173	239,128,208	240,429,401	235,904,889	238,380,565	240,156,992
2050	236,716,149	236,608,841	235,351,754	235,713,302	236,716,149	233,763,984	236,338,135	237,185,481

Table A - 4 Peru predicted coffee bean yield (Tons) from 2021-2050

	RCP45				RCP85			
	GE	HE	ICL	MI	GE	HE	ICL	MI
2021	292,488,537	299,760,263	302,938,002	294,764,482	296,179,139	302,977,352	297,501,815	300,035,347
2022	289,381,460	296,935,284	295,501,367	288,562,625	292,844,361	296,629,108	292,085,256	294,267,356
2023	283,267,852	287,518,840	288,883,106	286,078,514	283,722,098	290,020,322	287,395,788	289,390,747
2024	277,307,286	283,615,797	282,650,492	277,870,734	278,187,522	282,681,998	280,844,579	282,039,996
2025	275,143,363	280,424,114	278,845,557	271,776,958	274,707,491	278,705,451	274,525,836	276,993,301
2026	265,783,039	275,156,023	272,972,775	268,617,116	271,430,712	270,106,271	271,829,567	272,558,874
2027	260,436,029	263,150,244	265,801,173	260,956,145	265,431,277	267,707,842	264,082,264	263,624,472
2028	258,316,484	259,871,009	265,063,211	261,393,999	258,638,562	259,001,608	256,623,642	260,125,259
2029	252,041,573	253,657,783	257,437,781	255,042,090	252,002,117	256,084,921	253,613,491	254,854,211
2030	245,466,491	248,115,946	251,750,254	245,481,554	246,503,200	250,442,174	249,491,439	252,054,427
2031	245,862,823	247,346,485	248,370,079	244,160,659	245,961,546	251,934,522	248,427,600	245,718,691
2032	242,363,386	246,164,251	247,680,351	245,517,016	242,634,064	249,750,126	244,942,944	248,584,412
2033	241,145,393	244,421,370	244,557,107	242,902,063	245,004,090	247,346,695	243,772,893	245,865,091
2034	243,897,620	246,655,770	247,086,540	245,895,612	241,852,186	246,937,329	245,995,937	244,961,255
2035	243,574,374	244,282,232	244,866,529	241,182,402	241,229,004	242,126,810	242,343,028	242,263,947
2036	240,888,880	244,917,660	247,490,844	239,256,167	241,809,096	243,724,472	240,369,665	243,423,950
2037	241,335,625	242,130,039	245,577,743	240,641,341	239,279,132	240,400,416	240,249,409	241,247,722
2038	241,586,791	242,503,673	243,253,173	242,505,980	239,909,768	244,354,763	241,973,035	239,672,888
2039	239,609,137	240,486,330	241,452,396	239,895,418	239,045,228	244,850,247	240,047,243	242,446,525
2040	234,307,461	242,674,787	243,014,374	239,988,958	239,876,388	241,655,748	238,030,974	238,508,451
2041	234,795,959	241,880,134	239,701,598	237,742,662	236,630,804	240,905,391	239,878,809	238,171,379
2042	237,836,447	237,029,108	240,825,363	234,120,077	239,573,502	238,959,494	237,144,694	237,677,258
2043	236,261,913	238,585,181	238,267,597	236,848,765	236,757,369	237,898,419	236,111,635	235,786,909
2044	236,278,036	239,236,635	237,076,669	234,070,158	235,587,590	240,856,991	237,075,900	234,490,772
2045	232,405,061	235,695,600	237,117,057	236,736,584	235,856,112	235,338,023	232,629,676	238,811,638
2046	233,081,365	237,716,189	235,644,467	232,618,510	232,339,624	236,517,315	235,988,786	237,928,785
2047	229,975,061	233,637,713	233,033,992	229,840,003	231,942,561	233,480,649	231,983,000	236,700,632
2048	231,567,223	233,605,621	233,186,702	230,876,560	233,246,740	234,762,084	230,338,954	233,712,717
2049	232,010,378	233,138,834	232,314,976	230,699,009	230,572,419	231,481,004	234,618,539	232,057,839
2050	227,435,748	233,473,234	231,093,427	228,342,941	228,891,170	232,462,115	232,154,376	230,362,482

Table A - 5 Ethiopia predicted coffee bean yield (Tons) from 2021-2050

	RCP45				RCP85			
	GE	HE	ICL	MI	GE	HE	ICL	MI
2021	494,963,248	455,868,220	441,965,389	449,246,652	467,642,728	529,865,919	553,157,568	498,723,600
2022	491,958,854	464,099,082	447,760,226	460,771,051	464,280,121	539,067,003	560,410,304	510,896,716
2023	500,023,892	466,963,176	456,934,223	463,903,006	471,986,945	542,901,320	571,042,199	514,677,389
2024	511,651,142	473,734,259	459,412,677	472,601,702	483,255,982	550,642,624	574,978,551	524,024,804
2025	519,162,365	485,481,689	469,185,466	473,934,327	490,408,992	563,360,277	586,209,239	526,006,146
2026	525,509,838	494,133,444	481,169,307	482,833,180	496,398,251	572,982,254	599,650,978	535,553,717
2027	533,269,362	494,130,542	475,480,516	479,113,193	503,799,562	573,949,574	595,420,085	532,482,448
2028	534,396,052	498,503,680	478,895,777	489,738,548	504,568,038	579,292,935	600,293,245	543,756,521
2029	541,454,233	506,905,087	487,474,869	493,617,544	511,268,006	588,664,563	610,330,235	548,284,235
2030	549,796,993	510,961,963	491,792,388	509,721,382	519,252,552	593,691,662	616,105,652	565,036,790
2031	544,853,750	509,078,676	493,418,708	502,677,600	514,473,009	591,364,993	617,065,729	557,696,552
2032	549,033,798	508,753,708	487,534,776	500,284,847	518,816,757	590,596,645	610,515,553	555,007,341
2033	537,825,819	510,980,231	488,101,359	491,444,543	507,772,477	592,379,787	610,415,892	545,870,581
2034	535,583,882	502,015,013	488,043,742	495,155,903	505,694,240	582,971,188	609,692,031	549,285,484
2035	530,146,227	507,715,343	480,041,764	492,899,771	500,420,284	588,228,136	601,023,809	546,732,894
2036	533,878,785	491,313,908	478,229,855	488,154,476	504,316,542	571,383,321	598,545,656	541,691,142
2037	523,955,841	499,847,051	477,247,642	483,482,851	494,557,298	579,473,082	596,897,199	536,723,060
2038	524,609,643	497,063,756	469,372,282	485,107,531	495,374,800	576,246,406	588,355,595	538,051,282
2039	523,393,370	484,964,802	478,249,839	478,641,339	494,322,227	563,704,071	596,566,908	531,288,633
2040	516,433,190	490,363,301	468,228,956	479,327,863	487,525,747	568,659,188	585,879,782	531,678,701
2041	519,259,156	490,939,520	466,811,682	469,227,749	490,515,412	568,792,027	583,796,263	521,282,130
2042	518,955,365	480,860,121	464,173,289	470,021,979	490,375,321	558,269,246	580,491,627	521,779,902
2043	511,949,738	482,363,879	459,692,606	469,829,545	483,533,394	559,329,624	575,344,700	521,291,012
2044	510,387,391	473,182,799	461,787,056	473,994,726	482,134,746	549,705,163	576,772,906	525,159,735
2045	510,038,005	471,771,196	459,111,398	465,872,051	481,949,060	547,850,179	573,431,004	516,740,603
2046	500,827,660	463,905,202	454,768,802	463,376,759	472,902,415	539,540,803	568,422,165	513,948,853
2047	502,868,276	467,063,371	450,179,160	463,529,461	475,106,730	542,255,591	563,166,278	513,805,099
2048	498,899,968	466,345,307	449,437,030	452,303,944	471,302,122	541,094,146	561,757,905	502,283,124
2049	493,432,998	454,353,301	445,878,965	457,817,218	465,998,852	528,658,759	557,533,596	507,499,942
2050	488,140,973	454,115,866	446,102,606	455,085,420	460,870,526	527,977,943	557,090,993	504,471,687

Table A - 6 Suitable harvested area (ha) from 2021 to 2050

	Colombia	Brazil	Honduras	Peru	Ethiopia
2021	922,267	1,764,135	341,721	380,850	703,555
2022	919,094	1,727,870	334,442	373,699	712,779
2023	915,921	1,691,604	327,163	366,549	722,004
2024	912,748	1,655,339	319,883	359,399	731,229
2025	909,575	1,619,074	312,604	352,249	740,453
2026	906,402	1,582,809	305,325	345,098	749,678
2027	903,229	1,546,544	298,046	337,948	758,903
2028	900,057	1,510,278	290,767	330,798	768,127
2029	896,884	1,474,013	283,488	323,647	777,352
2030	893,711	1,437,748	276,209	316,497	786,577
2031	889,414	1,423,859	273,442	315,389	782,361
2032	885,117	1,409,970	270,674	314,280	778,146
2033	880,821	1,396,082	267,907	313,171	773,930
2034	876,524	1,382,193	265,140	312,063	769,714
2035	872,227	1,368,304	262,373	310,954	765,499
2036	867,931	1,354,415	259,606	309,846	761,283
2037	863,634	1,340,526	256,839	308,737	757,068
2038	859,337	1,326,638	254,072	307,629	752,852
2039	855,040	1,312,749	251,305	306,520	748,637
2040	850,744	1,298,860	248,538	305,411	744,421
2041	846,447	1,284,971	245,771	304,303	740,205
2042	842,150	1,271,082	243,004	303,194	735,990
2043	837,854	1,257,194	240,237	302,086	731,774
2044	833,557	1,243,305	237,470	300,977	727,559
2045	829,260	1,229,416	234,703	299,869	723,343
2046	824,964	1,215,527	231,935	298,760	719,128
2047	820,667	1,201,638	229,168	297,651	714,912
2048	816,370	1,187,750	226,401	296,543	710,696
2049	812,074	1,173,861	223,634	295,434	706,481
2050	807,777	1,159,972	220,867	294,326	702,265

Table A - 7 Unit roasting cost in roasting centers

Roasting Centers	Cost($/kg)
Kent, WA	1.5
Minden, NV	1.5
York, PA	1.5
Gaston, SC	1.5
Augusta, GA	1.5

Table A - 8 Unit ocean shipping cost ($/kg) from source countries to ports

	Everglades FL	New Orleans LA	New York NY	Savannah GA	Seattle WA	Norfolk VG	Houston TX	Charleston SC	Oakland CA	Jacksonville FL
Honduras	0.11	0.08	0.09	0.11	0.08	0.10	0.08	0.11	0.08	0.08
Peru	0.08	0.07	0.09	0.08	0.06	0.09	0.08	0.08	0.05	0.07
Colombia	0.04	0.04	0.07	0.04	0.04	0.07	0.04	0.04	0.09	0.04
Brazil	0.11	0.13	0.08	0.11	0.15	0.08	0.13	0.10	0.14	0.11
Ethiopia	0.14	0.13	0.12	0.14	0.10	0.12	0.14	0.13	0.10	0.14

Table A - 9 Unit transportation cost ($/kg) from ports to roasting centers

	Kent, WA	Minden, NV	York, PA	Gaston, SC	Augusta, GA
Everglades, FL	1.40	1.00	0.56	0.27	0.26
New Orleans, CA	0.93	0.93	0.64	0.35	0.32
New York, NY	1.20	0.94	0.10	0.33	0.35
Savannah, GA	1.40	0.98	0.34	0.15	0.13
Seattle, WA	0.07	0.35	1.40	1.40	1.40
Norfolk, VG	1.40	1.00	0.15	0.18	0.21
Houston, TX	0.97	0.67	0.79	0.48	0.45
Charleston, SC	1.40	1.00	0.32	0.12	0.15
Oakland, CA	0.55	0.13	1.50	1.40	1.40
Jacksonville, FL	1.20	0.90	0.40	0.12	0.11

Table A - 10 Unit transportation cost ($/kg) from roasting centers to states

Roasting centers	States					
	AI	AZ	AK	CA	CO	CT
Kent, WA	1.3285	0.6633	1.1502	0.5312	0.6370	1.4960

Table A - 10 Continued

Roasting centers	States					
Minden, NV	1.2779	0.4329	1.0481	0.2570	0.5269	1.5165
York, PA	0.3985	0.7747	0.4819	0.9028	0.6290	0.1536
Gaston, SC	0.1787	0.7612	0.3614	0.8884	0.8700	0.4246
Augusta, GA	0.1503	0.7398	0.3329	0.8670	0.8388	0.4524
	DE	DC	FL	GA	ID	IL
Kent, WA	1.4443	1.3455	1.5246	1.2805	0.2635	1.0145
Minden, NV	1.4619	1.4005	1.3229	1.2660	0.3233	0.9158
York, PA	0.1297	0.1093	0.5651	0.3332	0.9802	0.2937
Gaston, SC	0.3038	0.2238	0.2796	0.0945	1.1439	0.4474
Augusta, GA	0.3317	0.2486	0.1831	0.0685	1.1161	0.4162
	IN	IA	KS	KY	LA	ME
Kent, WA	1.1000	0.8586	0.8296	1.1635	1.2705	1.5915
Minden, NV	1.0308	0.7952	0.8187	1.0725	1.1574	1.6173
York, PA	0.3113	0.3797	0.4608	0.2137	0.5406	0.2534
Gaston, SC	0.3408	0.5968	0.5667	0.2098	0.3587	0.5243
Augusta, GA	0.3470	0.5639	0.5361	0.2150	0.3302	0.5522
	MD	MA	MI	MN	MS	MO
Kent, WA	1.3540	1.5407	0.8157	0.8134	1.2691	0.9739
Minden, NV	1.4097	1.5637	0.8591	0.8804	1.1443	0.8752
York, PA	0.1008	0.2023	0.4044	0.4104	0.4664	0.3553
Gaston, SC	0.2386	0.4732	0.6479	0.6564	0.2893	0.4827
Augusta, GA	0.2633	0.5011	0.6234	0.6864	0.2609	0.4515
	MT	NE	NV	NH	NJ	NM
Kent, WA	0.3101	0.8158	0.3419	1.5298	1.4383	0.6492
Minden, NV	0.6477	0.7057	0.0884	1.5521	1.4556	0.5459
York, PA	0.8873	0.4521	0.8873	0.2293	0.1275	0.7674
Gaston, SC	1.0958	0.6505	0.9690	0.5003	0.3371	0.8492
Augusta, GA	1.0680	0.6194	0.9476	0.5298	0.3649	0.8186
	NY	NC	ND	OH	OK	OR
Kent, WA	1.4441	1.4001	0.6604	1.1631	0.8916	0.1098
Minden, NV	1.4617	1.4317	0.9751	1.1177	0.7862	0.3693
York, PA	0.0953	0.1695	0.6280	0.1516	0.5424	1.1759
Gaston, SC	0.3663	0.1082	0.7909	0.2676	0.5634	1.3702
Augusta, GA	0.3941	0.1329	0.8204	0.2925	0.5329	1.3424
	PA	RI	SC	SD	TN	TX
Kent, WA	1.3765	1.5341	1.3758	0.6863	1.1615	0.9573

Table A - 10 Continued

Roasting centers	States					
Minden, NV	1.3903	1.5567	1.3785	0.9541	1.1561	0.8641
York, PA	0.0888	0.1866	0.2612	0.6093	0.3249	0.6557
Gaston, SC	0.2994	0.4575	0.0670	0.7652	0.2068	0.6111
Augusta, GA	0.3255	0.4854	0.1269	0.7375	0.1807	0.5807
	UT	VT	VA	WA	WV	WI
Kent, WA	0.3882	1.5250	1.3908	0.0864	1.2427	0.9440
Minden, NV	0.3344	1.5471	1.4276	0.4795	1.2606	0.9395
York, PA	0.7051	0.2537	0.0929	1.1583	0.1647	0.3140
Gaston, SC	0.7713	0.5247	0.1751	1.3901	0.1693	0.5169
Augusta, GA	0.7499	0.5525	0.1999	1.3624	0.1924	0.5500
	WY					
Kent, WA	0.6575					
Minden, NV	0.6919					
York, PA	0.6748					
Gaston, SC	0.7907					
Augusta, GA	0.7630					

Table A - 11 Annual percentage of coffee beans exported

Country	Percentage
Honduras	95%
Peru	96%
Colombia	85%
Brazil	70%
Ethiopia	56%

Table A - 12 Coffee beans demand in state in 2021

State	Demand	State	Demand
AL	3,250,334.32	NE	2,217,875.19
AZ	18,660,742.94	NV	9,674,524.52
AR	2,103,157.50	NH	1,108,937.59
CA	107,872,860.33	NJ	9,980,438.34

Table A – 12 Continued

State	Demand	State	Demand
CO	18,393,068.35	NM	2,906,181.28
CT	4,703,424.96	NY	24,664,301.63
DE	955,980.68	NC	12,924,858.84
DC	3,479,769.69	ND	497,109.96
FL	26,538,023.77	OH	14,454,427.93
GA	12,465,988.11	OK	3,020,898.96
ID	2,562,028.23	OR	13,727,882.62
IL	21,987,555.72	PA	13,651,404.16
IN	8,450,869.24	RI	1,032,459.14
IA	3,403,291.23	SC	5,009,338.78
KS	3,594,487.37	SD	955,980.68
KY	4,435,750.37	TN	6,883,060.92
LA	3,212,095.10	TX	39,845,274.89
ME	1,147,176.82	UT	3,862,161.96
MD	9,827,481.43	VT	305,913.82
MA	10,439,309.06	VA	16,519,346.21
MI	10,821,701.34	WA	28,947,095.10
MN	7,036,017.83	WV	955,980.68
MS	1,223,655.27	WI	5,544,687.96
MO	7,188,974.74	WY	879,502.23
MT	1,376,612.18		

Table A - 13 Percentage of coffee beans exported to the United States

Country	Percentage
Colombia	43%
Brazil	19.5%
Honduras	27%
Peru	27%
Ethiopia	11%

Table A - 14 Number of Starbucks locations by state

State	Locations	Percentage
California	3032	20%
Texas	1202	7%
Florida	780	5%
Washington	778	5%
New York	695	4%

Table A - 15 Roasting center capacity in 2021

Roasting center	Capacity
Kent, WA	56,439,927.46
Minden, NV	284,866,044.75
York, PA	108,076,339.53
Gaston, SC	115,281,306.31
Augusta, GA	132,186,727.68

VITA

Rui Zhou was born in Sichuan, China, on February 28, 1996. She enrolled into Nanchang Aviation University, major in Industrial Engineering in 2014. She participated in a research on the linkage mechanism of auto parts industry and logistics industry in her undergraduate school. She plans to graduate from the University of Tennessee with a Master of Science degree in Industrial and Systems Engineering in December 2020. She was admitted to the Industrial and Systems Engineering Ph.D. program in University of Tennessee in fall 2020.